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Review

Plant virus directed fabrication of nanoscale materials and devices

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ABSTRACT

Bottom-up self-assembly methods in which individual molecular components self-organize to form functional nanoscale patterns are of long-standing interest in the field of materials sciences. Such self-assembly processes are the hallmark of biology where complex macromolecules with defined functions assemble from smaller molecular components. In particular, plant virus-derived nanoparticles (PVNs) have drawn considerable attention for their unique self-assembly architectures and functionalities that can be harnessed to produce new materials for industrial and biomedical applications. In particular, PVNs provide simple systems to model and assemble nanoscale particles of uniform size and shape that can be modified through molecularly defined chemical and genetic alterations. Furthermore, PVNs bring the added potential to "farm" such bio-nanomaterials on an industrial scale, providing a renewable and environmentally sustainable means for the production of nano-materials. This review outlines the fabrication and application of several PVNs for a range of uses that include energy storage, catalysis, and threat detection.

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Introduction

Advances in nanotechnology offer significant improvements in a wide range of applications that include light weight materials with greater strength, increased energy efficiency from electronic devices, and better sensors for a range of environmental, pharmaceutical and manufacturing uses. A key challenge to achieving these improvements is the ability to assemble and pattern diverse components into functioning nanoscale devices. Current “top-down” semiconductor processing techniques such as lithography have limitations with respect to the scale of assembly, complexity of the desired nanofeatures and cost of synthesis (Fan et al., 2013). In comparison, biological systems function almost exclusively through the molecular assembly of diverse components to produce molecular machines of incredible complexity. Microtubule kinesin and bacterial flagella motors are two examples of the types of “bottom up” self-assembly systems that are sought by engineers yet routinely produced at the nanoscale within biological systems (Browne and Feringa, 2006; Korten et al., 2010; Stock et al., 2012). However, the development of such sophisticated assembly systems requires new engineering advances that integrate or mimic these “bottom-up” self-assembly methods.

To achieve these advances scientists from biological and engineering disciplines have investigated the nanoscale structures of viruses as simple systems from which to develop design, synthesis and application strategies for the production and functionalization of self-assembling materials. Viruses have evolved exquisite macromolecular particles in which to store and protect their genomes. These particles also play critical roles in cell entry, virus movement and in many instances virus replication. The functional demands placed upon these particles has resulted in the development of extremely uniform and complex molecular structures that are derived from the self-assembly of a limited number of molecular building blocks. In fact, virus particles represent ideal nanomachines that not only self-assemble into macromolecules of defined shape and size but also function as environmental sensors for the controlled release of their genomes upon cell entry. The same virus particles also operate as information storage devices that carry genetic instructions to produce the next generation of components required for self-assembly. These combined features have led to the incorporation of virus structures into an array of devices and applications that have broken new ground in the development of biomaterials (Douglas and Young, 1998; Shenton et al., 1999; Whaley et al., 2000). In particular, plant viruses have received significant interest as both models and materials for the establishment of strategies that combine biological processes with traditional top-down manufacturing systems. Characteristics that make many plant viruses attractive for these studies are their relative simplicity, including the lack of membranes, ease of purification and simple one or two protein capsid assemblies that are structurally well defined. In addition, genetic programmability and in vitro assembly systems permit the uniform production of particles with designer functionalities such as antigen display and analyte recognition. In this review we primarily focus on the application of plant virus-derived nanoparticles (PVN) as nanoscale scaffolds and containers for the development of materials and devices with unique functionalities. However, space constraints limit our ability to fully cover the diverse array of PVN applications currently being investigated. In addition, we have not attempted to fully address the considerable work being done in the application of PVN in vaccine development, bio-imaging and drug delivery. To address these deficiencies we recommend several additional reviews that cover the application of viruses and protein structures in nanotechnology and biomedicine applications (Alonso et al., 2013a; Fan et al., 2013; Franzen and Lommel, 2009; Li and Wang, 2014; Lomonossoff and Evans, 2014; Rong et al., 2011; Young et al., 2008).

PVN characteristics for biomaterial fabrication

Several features make plant viruses useful as scaffolds for the synthesis of nano-materials. First, their simple virions derived from the self-assembly of defined protein subunits are remarkably stable and are of uniform size and shape. The repeating patterns of amino acid side chains displayed by each protein subunit can function to direct the ordered nucleation of inorganics or chemical cross-linkers for the display of novel molecules on either the inner or outer virion surfaces. Second, the ability of these particles to self-assemble and remain monodispersed in solution permits their functionalization and analysis in bulk suspensions. In fact, studies have determined that virion particles such as *Paramecium bursaria chlorella virus* (PBCV-1) behave similar to nanosphere polymer colloids in suspension, allowing standard materials science approaches to be used for their analysis (Sirotkin et al., 2014). Third, the three-dimensional (3-D) structures for many of these viruses are known, permitting the design and targeting of specific moieties on or within the PVN as a means to add functionality. Fourth, genetic programming for the development of virions with directed structural and functional properties is possible, including the addition of unique amino acids, peptides and assembly profiles. Fifth, as biomaterials plant viruses can be produced at scale and in a renewable fashion. We are dependent upon biomaterials for many of the necessities and conveniences of everyday life. Most of these biomaterials including ethanol fuels, cotton and wood fibers are produced through modern agricultural practices and at a scale that makes these products extremely cost efficient. The ability to apply such large-scale cost effective practices to produce nanoscale materials represents an attractive method for industrial applications. Combined these traits have attracted a range of researchers with expertise ranging from agronomic production, virology, structural biology, colloid chemistry and microdevice fabrication to explore the potential application of these particles in materials and therapeutic applications.

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