

Hierarchical self-assembly of amphiphilic building blocks into various supramolecular architectures

Shib Shankar Dash*

Department of Chemistry, Govt. General Degree College, Salboni, Paschim Medinipur, 721516, West Bengal, India.
E-mail: shiba.chem@gmail.com

Received: February 15, 2018 | Accepted: April 12, 2018 | Published online: May 12, 2018

Abstract

Molecular self-assembly is a process to obtain a well defined structure from suitable starting materials. The study of self-assembly provides a fundamental understanding of the driving forces and co-operative interaction behind these processes. Among the plenty of molecules, an amphiphilic molecule, containing both hydrophilic and hydrophobic counter parts is one of the interesting building blocks to study the self-assembly processes. In this short review, the hierarchical self-assembly of amphiphilic molecules into various supramolecular architectures such as vesicles, spheres, flowers, tubes and fibrillar networks of nano- to micrometer dimensions and gels have been discussed.

1. Introduction

Building materials from the bottom up strategy is complementary to traditional top-down materials processing, but requires a deep understanding of the individual molecular structures, their assemblies, and dynamic behaviors. Self-assembly results in the preparation of highly complex molecular and supramolecular systems from relatively simple starting materials.^{1,2} Typically, self-assembled supramolecules are constructed by combining complementary pairs of two highly symmetric molecular components, thus reduces the probability for the formation of unwanted side products. Molecular self-assembly is driven by weak, non-covalent interactions notably hydrogen bonds, ionic bonds (electrostatic interactions), hydrophobic interactions, van der Waals interactions, and water-mediated hydrogen bonds.³ Hierarchical molecular self-assembly leading to various supramolecular architectures of nano- to micrometer dimensions such as fibres, vesicles, spheres, tubes, and porous microstructures have gained renewed interest in recent years owing to their diversified applications in drug delivery,⁴ cancer and inflammatory diseases,⁵ tissue engineering,⁶ pollutant capture,^{7,8} templating nanomaterials, etc. Different classes of amphiphiles molecules such as peptides,⁹ fatty acids,¹⁰ sophorolipids,¹¹ steroids,¹² sugars,¹³ polysaccharide,⁵ cholesterol, saponins have been reported containing both hydrophilic and hydrophobic counter parts in a balanced ratio. These amphiphiles spontaneously self-assembled to form various morphologies including micelles, fibers, rods, vesicular aggregates, etc..¹⁴ Reports during the last decade has shown that naturally occurring triterpenoids with varied number of hydroxyl and carboxyl groups can act

as amphiphiles and spontaneously self-assemble in different liquids yielding nano architectures.^{15,16} In amphiphiles, the hydrophilic and hydrophobic segment are linked through a covalent bond. In contrast to conventional amphiphiles, supra-amphiphiles are constructed on the basis of non-covalent interactions or dynamic covalent bonds.^{17,18} Starting from low molecular weight amphiphiles, polymeric amphiphiles are also possible. The self-assemblies obtained from polymeric amphiphiles have a larger capacity to incorporate guest molecules but the assembly from low molecular weight amphiphiles are comparatively dynamic in nature. Naturally occurring amphiphiles such as phospholipids, the main component of biological system are composed of one hydrophilic head and two hydrophobic tails. When exposed to water, it spontaneously self-assembles to form bilayer vesicular structure. In a similar way, synthetic amphiphiles possessing almost similar topology like phospholipids can also self-assemble. In this review the classification of amphiphiles and their self-assembly to different supramolecular architectures have been discussed.

2. Amphiphilic building blocks in supramolecular chemistry

2.1 Amphiphiles

Amphiphile is a chemical compound possessing both hydrophilic (*water-loving*, polar) and lipophilic (*fat-loving*) properties. This forms the basis for a number of areas of research in chemistry and biochemistry. Among the various building blocks for the study of self-assembly, an amphiphilic molecule, containing both hydrophilic and hydrophobic counter parts, is supposed to be powerful building blocks for the same.¹⁹ When amphiphiles are dispersed in water, the hydrophilic counterpart of the amphiphiles preferably interacts with the aqueous phase while the hydrophobic part tends to be directed in the air or in the nonpolar solvent. Therefore, the amphiphiles aggregate based on the repelling and coordinating forces between the hydrophilic and hydrophobic parts of the component molecules and the surrounding medium and leads to the formation of various well-defined molecular assemblies, such as micelles, vesicles, fibers, tubes, sheets (Figure 2) etc.²⁰ In aqueous media, lipid molecules self-assemble into diversified morphologies, depending upon their molecular shape and solution conditions such as lipid concentration, electrolyte concentration, pH and temperature.²¹

2.2 Classification of amphiphiles

Amphiphiles are classified in different categories (Figure 1) depending upon various criteria given below: (i) based on the charge of the head group amphiphiles are classified as ionic (cationic or anionic), non-ionic, zwitterionic and amphoteric (whose charge changes with pH); (ii) depending on number and type of connection of polar head groups/hydrophobic tails amphiphiles are classified as: (a) conventional single head/ single tail amphiphiles, (b) bola amphiphiles which contain two hydrophilic heads connected by a hydrophobic skeleton, (c) Gemini amphiphiles composed of two hydrocarbon chains and two polar heads linked by a spacer, (d) double and triple chain amphiphiles and (e) catanionic amphiphiles.

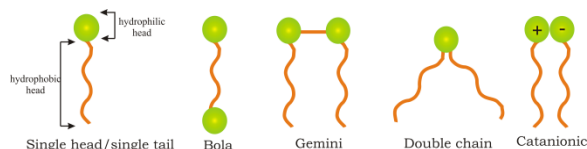


Figure 1: Classification of amphiphiles

3. Self-assembly of amphiphiles

Amphiphilic self-assemblies range from simple structures such as micelles, vesicles, micro emulsions and mono- and bi-layers to highly complex biological architectures such as membranes. Amphiphiles may undergo spontaneous self-assembly into micellar structures with distinct size and shape that may be useful as templates for generating nano materials and mimicking biomineralization processes.

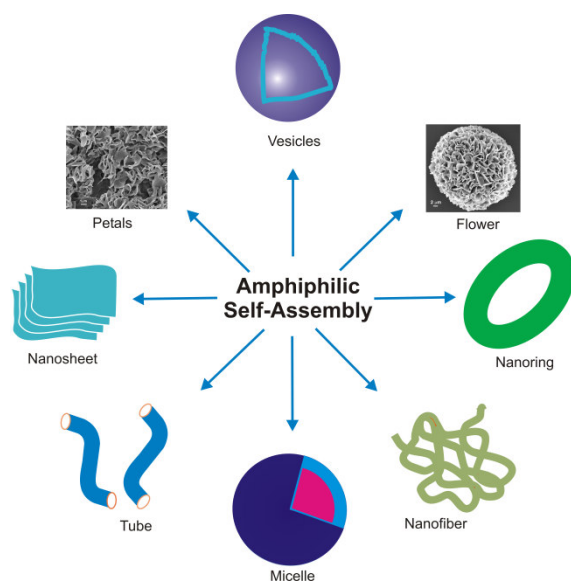


Figure 2: Self-assembly of amphiphiles into different supramolecular architectures

3.1 Micelles and Reverse micelle

A micelle or micella is an aggregate of surfactant molecules dispersed in a liquid. A typical micelle in aqueous solution forms an aggregate with the hydrophilic "head" regions in contact with surrounding solvent, sequestering the hydrophobic single-tail regions in the micelle centre. Micelles are small assemblies of 50-100 monomers. Micelles are formed spontaneously and reversibly by single head/ single tail amphiphiles above the *critical micelle concentration* (CMC). Generally, the shape of the micelles is spherical, but depending on surfactant geometry and other experimental variables they can be ellipsoids or long cylinders. Reverse micelles are nanometer-sized (1-10 nm) water droplets dispersed in organic media obtained by the action of surfactants. Surfactant molecules organize with the polar part to solubilize water and the non polar part remains in contact with the organic solvent. Reverse micelle are those where the hydrophobic tail pointed towards organic solvents like CHCl_3 and hydrophilic end remain directed towards the polar liquid like water (Figure 3).

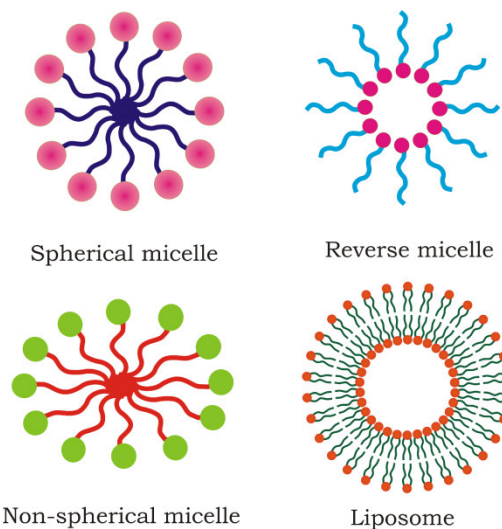


Figure 3: Various morphologies obtained through amphiphilic self-assembly.

3.2 Vesicles and liposome

Vesicles are spherical or ellipsoidal amphiphilic bi-layers in which the inner cavity contains the aqueous solution in which they are dispersed. Small sized vesicles spontaneously fuse together and finally get converted to larger vesicles (Figure 4). Generally vesicles are formed by naturally occurring phospholipids and synthetic lipids and commonly they are referred as liposome (Figure 3). Spontaneous self-assembly of synthetic peptides may also lead to the formation of vesicles in organic and aqueous solvents. Ajayaghosh et al. reported the formation of vesicles by the self-assembly of oligo (*p*-phenyleneethynylene)s.²² A liposome is an artificially-prepared spherical vesicle composed of a lipid bi-layer. The liposome can be used as a

vehicle for carrying pharmaceutical drugs into the targeted cells. Liposome can be prepared by disrupting biological membranes.

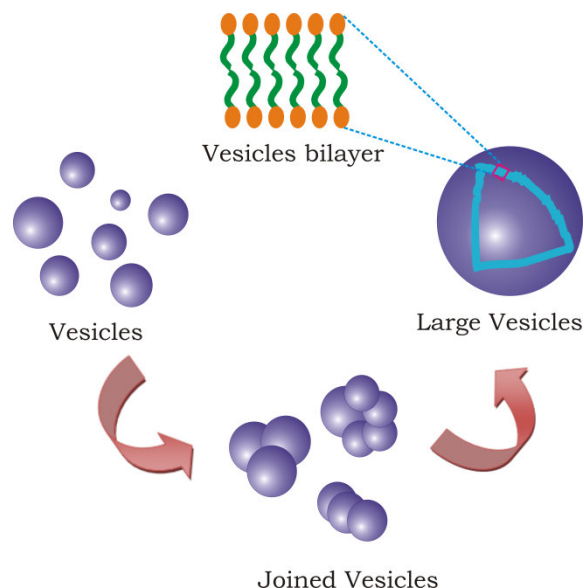


Figure 4: Mechanism of vesicle formation

3.4 Fibers

Generally self assembled fibrillar networks (SAFINs) are formed by dissolving the amphiphiles in aqueous solution, organic liquids or organo-aqueous mixtures under hot condition and then allowing the resulting solution to cool at room temperature (Figure 5). These nanofibers can be classified into micellar based aggregates and bi-layer sheet based aggregates.²³ A well known example of micellar fibers formed by some of the members of *N*-alkylaldonamides was examined by Fuhrhop and co-workers. There are many examples in the literature where SAFINs are formed by the self assembly of peptides, bile acid esters, lipids, etc.

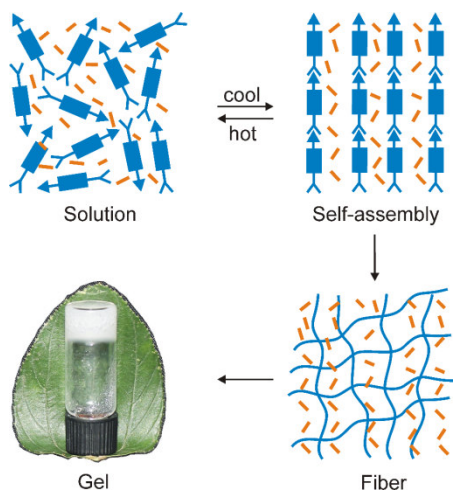


Figure 5: Schematic representation of fibrillar gel formation.

3.5 Nano Sheet, Tube, Ring and Spheres

The self-assembly of amphiphiles which are based on distorted sheet-like bi-layer membrane with high aspect ratio are very interesting. This type of self-assemblies yields tube, ribbon etc. A nanosheet is a two-dimensional nanostructure with thickness in a scale ranging from 1 to 100 nm. A typical example of nanosheet is graphene, the thinnest two-dimensional material (0.34 nm) in the world. It only consists of single layer of carbon atoms with hexagonal lattices. The shape of the nanosheet, tube, ring and spheres is given in Figure 2.

4. Conclusion

Development of new building blocks for the study of self-assembly properties holds the key for future science and technology. In recent years, tremendous research efforts have been made on studying the self-assembly properties of different classes of amphiphiles and their diversified applications. In spite of large documentation on amphiphiles, Scientist continue their investigations on the design newer types of amphiphiles with newer applications. Newer building blocks ranging from short peptides, bi- or tri-block copolymers to complex DNA structures, lipids and proteins have been developed for the study of self-assembly system. Building blocks, obtainable from renewable resources such as plants, yielding self-assembled materials via self-assembly process, holds the key for a sustainable development without compromising the needs of the future.

Author Information



Dr. Shib Shankar Dash received his B.Sc. in Chemistry from Midnapore College, Vidyasagar University, India in 2007 and M.Sc. in Chemistry from Vidyasagar University, India in 2009. He is completed his Ph.D in the year 2015 from the Department of Chemistry and Chemical Technology, Vidyasagar University, Midnapore, India under the supervision of Professor Braja Gopal Bag. Currently, he has joined as Assistant Professor at the department of Chemistry, Govt. General Degree College, Salboni, Paschim Medinipur. His research interest involves the utilization of plant based renewable chemicals in Supramolecular Chemistry and nanoscience.

5. References

1. S. Zhang, *materialstoday*, **2003**, 20.
2. M. Grzelczak, J. Vermant, E. M. Furst, L. M. Liz-Marzán, *Acs Nano*, **2010**, 4, 3591.
3. P. Gale, J. Steed, Wiley-VCH Verlag GmbH & Co, KGaA, Weinheim, **2012**
4. A. Barnard, P. Posocco, S. Pricl, M. Calderon, R. Haag, M. E. Hwang, V. W. T. Shum, D. W. Pack,

-
- D. K. Smith, *J. Am. Chem. Soc.* **2011**, 133, 20288–20300.
5. X. Yang, X. Shi, R. D'arcy, N. Tirelli, G. Zhai, *J Control Release*. **2017**, 272, 114-144
6. K. Y. Lee, D. Mooney, *J. Chem. Rev.* **2001**, 101, 1869–1880.
7. R. S. Jadhav, P. K. Vemula, R. Kumar, S. R. Raghavan, G. John, *Angew. Chem., Int. Ed.* **2010**, 49, 7695–7698.
8. B. G. Bag, S. S. Dash, *Langmuir*, **2015**, 31, 13664-13672.
9. D. Das, T. Kar, P. K. Das, *Soft Matter*, **2012**, 8, 2348–2365.
10. M. Delamplate, F. Jerome, J. Barrault, J. P. Douliez, *Green Chem.* **2011**, 13, 64–68.
11. S. Zhou, C. Xu, J. Wang, W. Gao, R. Akhverdiyeva, V. Shah, R. Gross, *Langmuir* **2004**, 20, 7926–7932.
12. Nonappa, U. Maitra, *Soft Matter*, **2007**, 3, 1428–1433.
13. H. Kobayashi, A. Friggeri, K. Koumoto, M. Amaike, S. Shinkai, D. N. Reinhoudt, *Org. Lett.* **2002**, 4, 1423–1426.
14. M. Antonietti, S. Froster, *Adv. Mater.*, **2003**, 15, 1323.
15. B.G. Bag, R. Majumdar, *Chem. Rec.*, **2017**, 17, 841-873.
16. B. G. Bag, A. C. Barai, S. N. Hasan, S. Das, C. Garai, S. Ghorai, S. K. Panja, *Prayog. Ras.*, **2017**, 1(3), 61 -68.
17. X. Zhang, C. Wang, *Chem. Soc. Rev.* **2011**, 40, 94–101.
18. Y. J. Jeon, P. K. Bharadwaj, S. Choi, J. W. Lee, K. Kim, *Angew. Chem., Int. Ed.* **2002**, 41, 4474–4476.
19. J. N. Israelachvili, D. J. Mitchell, B. W. Ninham, *J. Chem. Soc., Faraday Trans. 2* **1976**, 2, 1525.
20. H. Ringsdorf, B. Schlarb, J. Venzmer, *Angew. Chem., Int. Ed.* **1988**, 27, 113.
21. J. N. Israelachvili, *Intermolecular and Surface Forces*; Academic Press: New York, **1985**.
22. A. Ajayaghosh, R. Varghese, S. Mahesh, V. K. Praveen, *Angew. Chem., Int. Ed.*, **2006**, 45, 7729.
23. H. Ihara, M. Takafuji, T. Sakurai, "Self- Assembled Nanofibers" from *encyclopedia of Nanoscience and nanotechnology*, American scientific publishers, California, **2004**, 9, 473.