2
Supramolecular Structures

Pieter Stroeve

2.1
Introduction

Well before the current fascination with nanoscience and nanotechnology, scientists were studying phenomena on the nanoscale. For example, colloid and surface scientists have been interested in colloidal dispersions, micelles, vesicles, and surface modification by a layer of molecules for more than 150 years. Cell biologists have studied the organized structures existing in living cells since the nineteenth century. These structures are now known to have intricate geometry on the nanoscale, with very specialized molecular functions such as transport, synthesis, and energy generation. Plant cells have very complex internal structures similar to living cells. Most of our food is ultimately derived from plants, and studies of plant cells on the nanoscale are giving microbiologists, plant scientists, food scientists, and engineers new information about how to modulate plant growth, plant diversification, harvesting, food processing, and food preservation. For food science, nanotechnology has a different meaning from that encountered in other disciplines, such as the fabrication of integrated circuits for high-speed computers. For food, nanotechnology can be defined as the understanding of food on the nanoscale and translating this knowledge into new processes for food modification and enhancement of food value and preservation. This approach is one of the greatest challenges in food science and engineering.

The understanding of plant cells on the nanoscale is the fundamental basis for developing the nanoscience and nanotechnology to produce new and improved foods. By way of example, pulsed electric field (PEF) processing may be mentioned. PEF processing has been used to increase the rate of dehydration of water from fruits to produce dried fruit. It is well known that for certain conditions PEF can irreversibly open nanopores in the plant cell membranes (electroporation) and water can then escape more rapidly from the plant cell. The cell membrane is made up of a lipid bilayer, and lipids have self-assembly properties. The optimal conditions for PEF to increase dehydration for different fruits are not known. Likewise, the optimum nanopore size in the cell plant membrane and the number of openings per unit area of membrane are not known. Although there

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is now some knowledge about the response of the lipid bilayer to PEF, in a cell membrane proteins are associated with the lipid bilayer and they change the properties of the cell membrane significantly. Thus the study on PEF and its effect on plant cell membranes on the nanoscale can give important information that would be useful for making decisions on PEF processing of plant materials used for food.

In addition to the drying of fruits and vegetables, PEF is also useful in killing bacteria in process water streams by making the membranes of bacteria leaky. Another application of PEF that has been explored is enzyme deactivation. Further, reversible electroporation may provide an opportunity to introduce desirable components (color, flavor, nutrients, antioxidants) or remove valuable components while damage to the plant is reversible.

Another process that is receiving considerable interest is high-pressure processing of foods. In this process, food is treated at elevated pressures of the order of 6000 atm. The purpose of the treatment is to inactivate bacteria and to change the food quality. The precise effects of high-pressure processing on plant cell structures and properties are not known but are currently under study by a number of groups.

The study of the properties and functions of nanostructures in plant cells and their changes due to processing is of utmost importance to develop the database for devising new food processes. The molecules in plant cells inherently can self-assemble into structures and this process of self-assembly will be treated in this chapter.

2.2 Self-Assembly

Self-assembly is the process in which a disordered system of molecules spontaneously forms an organized structure or pattern that is at equilibrium or in a quasi-equilibrium state. A typical example is when surfactant molecules dissolved in water self-assemble to form micelles. A typical surfactant is sodium dodecyl sulfate (SDS), shown in Figure 2.1, which is an anionic surfactant. A surfactant contains both an "oil-loving" hydrocarbon chain and a "water-loving" hydrophilic headgroup. This gives the surfactant molecule amphipathic ("being of two kinds") properties, in that the surfactant can be in either an aqueous or a hydrophobic

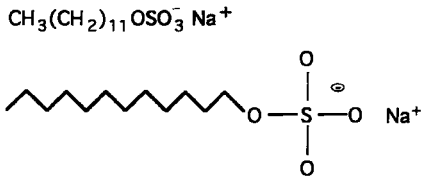

Figure 2.1 The chemical structure of sodium dodecyl sulfate.

environment. In an aqueous environment, SDS can self-assemble its hydrocarbon chains into a micellar aggregate.

In self-assembly, the organized structure or pattern formed has a reduced free energy compared to the initial state of the disorganized molecules. The specific molecular interactions existing between the molecules, before and after the spontaneous change, lead to the lowering of the overall free energy. Self-assembly processes in plant cells often take place at constant temperature and ambient pressure in an aqueous environment. For a spontaneous process to take place at constant temperature and pressure, the second law of thermodynamics states that the Gibbs free energy change between the initial state of a mixture of molecules, and the final state of some organized molecules, must be equal to or less than zero:

$$\Delta G \leq 0. \tag{2.1}$$

Since the Gibbs free energy is related to the change of enthalpy and entropy, Equation 2.1 can be changed to

$$\Delta G = \Delta H - T\Delta S \leq 0, \tag{2.2}$$

where H is the enthalpy, S is the entropy, and T is the absolute temperature. It can be inferred from Equation 2.2 that a decrease in enthalpy and an increase in entropy favor the occurrence of the process. However, if one of the terms, that is, ΔH or $T\Delta S$, opposes the process, the other one must have an (over)compensating favorable contribution to allow for a spontaneous process. The process of self-assembly of molecules to form organized structures does lead to an overall increase of entropy if both the organizing molecules and the solvent molecules are considered. This phenomenon can be further understood by the fact that, for the initial state, the water molecules in contact with an individual organic molecule are organized around the organic molecule like a cage. The water cage is similar to a clathrate and has a crystal-like structure. Upon self-assembly of the organic molecules (with themselves), the initial state and order of the water molecules around the individual organic molecules is changed, and the water molecules now in their final state are more random than before and are more like bulk water. Thus, even though the organic molecules have increased order and decreased entropy, the *net* entropy of the system has increased due to the increase in disorder and greater increase in entropy of the water molecules.

The spontaneous and reversible organization of molecular units into ordered structures occurs by non-covalent molecular interactions. The molecular interactions include van der Waals forces, hydrogen bonding, π–π bonds, and ionic interactions. These molecular interactions are often called weak interactions because their energies are considerably weaker (by a factor of 10 or more) than covalent or other bonds. Nevertheless, weak interactions play a very important role in nature. Weak interactions are responsible for the state of a pure component, such as the liquid or solid state versus the gaseous state. Obviously, weak interac-

tions are of great importance in biological systems, such as the self-assembly of organized structures in plant cells. Examples of organized structures in biology are self-assembled monolayers, lipid bilayers, micelles, and vesicles. The folding of peptide chains into functional proteins and enzymes is another example of structures in biology and occurs in plant cells. The weak interactions are also responsible for the possibility that the organized structures can undergo changes due to a change in thermodynamic variables, and return to the original structure if the thermodynamic conditions return to the original values, that is, the structures can show a degree of reversibility. The weak forces allow the structure to change, effectively seeking a new minimum free energy, depending on the existing thermodynamic conditions. Thus the properties of organized structures can change depending on the thermodynamic conditions. In terms of applications, such as food processing using plant materials, it makes external control of induced changes by processing steps such as temperature, pressure, electric field, and so on more difficult and troublesome because one needs to fully understand not only the structural changes that occur on the nanoscale but also the change in the properties on the nanoscale level and the change in the overall properties on the macroscopic level. On the other hand, it opens exciting new opportunities to change the properties of foods and the possibility to create new value-added foods.

It is possible for chemical reactions to cause molecules to self-assemble. An example is the chemisorption of molecules on a surface to form an organized monolayer. The driving force for self-assembly is the change in enthalpy due to the chemical transformation. This type of self-assembly is not reversible.

Before considering plant cells and self-assembled structures, one should understand that the complexity of molecules that can self-assemble is of great importance. The chemical composition of molecules, their size and shape play important roles in what type of organized structures can be created. Because of this complexity, a wide variety of nano- and mesoscopic structures can be formed depending on the type of molecules involved. Further, it is not necessary that the molecules are all the same: mixtures of different molecules (composition, molecular weight, shape, size, and charge) can self-assemble into organized structures. Properties associated with the structures depend on the nature of the structure and the types of molecule that make up the structure. Nature has learned to exert fine control on the formation of cellular structures with specific functions and properties, by choosing the appropriate precursors to self-assemble into the desired structure. These structures can be called supramolecular assemblies.

From a historical point of view, researchers in the discipline of chemistry were the first to explore the field of supramolecular chemistry, the assembly of synthesized molecules that can arrange into precise, well-organized structures. The synthesis of special molecules that can give rise to supramolecular assemblies is known as supramolecular chemistry. Supramolecular assemblies include molecular self-assembly, folding, molecular recognition, and host–guest chemistry (enzyme–substrate). The principles of supramolecular chemistry and supramolecular assembly are similar to what is done by nature in biological systems. In

both situations, molecules can interact because of weak molecular interactions. The folding of two single-stranded deoxyribonucleic acid (DNA) chains into a double helix is a supramolecular assembly and it is a consequence of weak interactions. The base-pairing in the DNA double helix formation is an example of molecular recognition that is solely due to weak molecular interactions. The study of non-covalent interactions is important in many biological systems. Self-assembly is crucial to the function of cells. An example is the self-assembly of lipids to form membranes, the formation of double helical DNA, and the assembly of proteins.

2.3 Plant Cells

Plant cells are eukaryotic cells that have distinctive, organized structures. A plant cell is shown in Figure 2.2. Like all cells, plant cells have a cell membrane, which has as a fundamental building block the lipid bilayer. It is known as the plasma membrane. However, plant cells contain a number of specialized structures. Plant cells have a cell wall, which provides the cell with structural support. A major function of the cell wall is to act as a pressure vessel to prevent over-expansion of the cell when water enters. Another role of the cell wall is to support the plant and to confer flexibility and tensile strength. Lignocellulose is the primary building block of plant cell walls. The cell wall is mainly composed of cellulose, hemicellulose, lignin, and smaller amounts of pectin, protein, and extractives (soluble non-structural materials such as non-structural sugars, nitrogenous material, chlorophyll, and waxes). The composition of these constituents may vary from one plant species to another. In addition, the ratio of the various constituents within a single plant varies with its age, stage of growth, and other conditions. Cellulose is the main structural constituent in plant cell walls and is found in an organized fibrous structure. This linear polymer consists of D-glucose subunits linked to each other by β-(1 → 4)-glycosidic bonds. Cellobiose is the repeating unit established through this linkage and it constitutes cellulose chains. The long-chain cellulose polymers are linked together by hydrogen and van der Waals interactions and

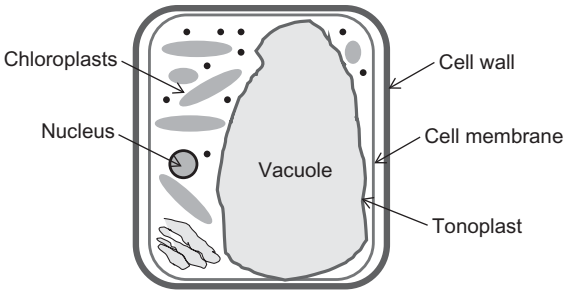

Figure 2.2 Schematic diagram of a typical plant cell. The vacuole can occupy from 70% to 90% of the interior of the cell.

cause the cellulose to be packed in microfibrils. Hemicelluloses and lignin cover the microfibrils. Cellulose in cell walls is present in both crystalline and amorphous forms. Crystalline cellulose forms the major proportion of cellulose, while there is a small percentage of non-organized cellulose chains, which form amorphous cellulose.

There are pores present in the cell wall, which are known as plasmodesmata. In the pores, the plasmalemma and endoplasmic reticulum of adjacent cells are continuous, which allows for cell-to-cell communication, which includes the transport of species.

Another specialized structure in the plant cell is a large central vacuole, which is completely enclosed by the tonoplast membrane. Like all biological membranes, the lipid bilayer is the building block that forms the tonoplast, although the tonoplast composition and properties are different from those of the cell membrane. The vacuole is filled with an aqueous mixture called the sap. The vacuole's membrane controls the movement of molecules between sap and the remaining fluid in the plant cell, the cytoplasm, which is known as the cytosol. The vacuole stores nutrients and digests waste materials and controls the cell's turgor.

Like many other cells, the plant cell contains mitochondria, Golgi vesicles, the Golgi body, small membrane vesicles, a nucleolus surrounded by a nuclear envelope containing nuclear pores, smooth endoplasmic reticulum, rough endoplasmic reticulum, ribosomes, and so on. The plant cell further contains starch grains, which serve as a storage of nutrients for the cell.

In the plant cell are plastids, which are organelles that serve as the site of synthesis and storage of important chemical compounds used by the cell. Plastids are responsible for photosynthesis, for the storage of products like starch, and for the synthesis of molecules, such as lipids, which are used as cellular building blocks and for the function of the plant cell. A structure of a typical lipid is shown in Figure 2.3, while the chemical structure of a phosphatidylcholine (lecithin) is shown in Figure 2.4. Lipids contain a hydrophilic head-group and two alkane chains. A double bond in a chain will cause a kink and has implications for the packing of the lipid in a lipid bilayer. Straight chains can pack tighter, leading to greater order of the bilayer, but less fluidity. Lipids with a kink in the chain cannot pack tightly in lipid bilayers, leading to more fluid-like behavior of the bilayer.

2.4 Organized Self-Assembled Structures

2.4.1 Langmuir Layers

The simplest organized structure is a monolayer of molecules organized at an interface. The study of monolayers at an interface can be done simply by using a Langmuir trough, also known as a Langmuir–Blodgett trough. Ultrapure water is placed in a Langmuir trough, and then a minute amount of a solution of a surface-

Figure 2.3 Structure of a typical lipid.

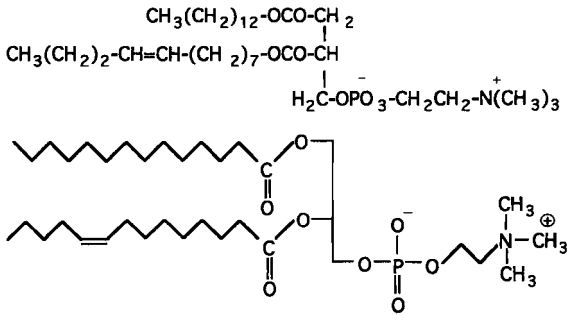

Figure 2.4 Chemical structure of phosphatidylcholine.

active species (e.g., surfactant, fatty acid or phospholipid) is administered to the air–water interface with a microsyringe. The solution is usually the surface-active species dissolved in a volatile, non-surface-active solvent such as hexane. By using the microsyringe, a known volume of the solution can be brought to the air–water interface by a series of small drops. The solution spreads rapidly (flashes) on the

interface, due to the positive spreading coefficient of the solvent, which causes the surface-active species to be distributed on the air–water interface. At the same time, the solvent evaporates due to its high vapor pressure, so that the surface-active species is the only one left on the air–water interface.

The Langmuir trough contains a movable barrier that divides the air–water interface. By moving the barrier, the surface area of the air–water interface and consequently the surface concentration of the surface-active species can be changed. The monolayer of surface-active species is known as the Langmuir layer and it lowers the surface tension (surface energy) of the air–water interface. An increase in the surface concentration, due to the barrier movement, can further lower the surface tension. The surface tension can be continuously measured by a Wilhelmy plate as shown in Figure 2.5. On the molecular scale, when the barrier compresses the surface-active species at the air–water interface, the surface-active molecules will arrange in an ordered layer, with the head-groups associating with the water and the hydrophobic tails aligned and sticking out of the interface. The Langmuir layer can be transferred to a solid substrate by dipping the substrate through the air–water interface. Repeated transfer of the solid substrate through the air–water interface can transfer multiple organized layers of the surface-active species to the substrate. Transferred molecular layers on a solid substrate are known as Langmuir–Blodgett layers and these layers can be readily studied by surface analytical instrumentation such as infrared (IR) spectroscopy, surface plasmon resonance (SPR), and atomic force microscopy (AFM).

2.4.2 Lipid Bilayers

The lipid bilayer is a membrane made up from lipid molecules. The lipid bilayer is a fundamental component of all biological membranes and is essential to life. Its structure was discovered in 1925 by Gorter and Grendel, who compared the surface area of human red blood cells with that of a known amount of lipids in a Langmuir trough. Gorter and Grendel found that the area of lipids from a known

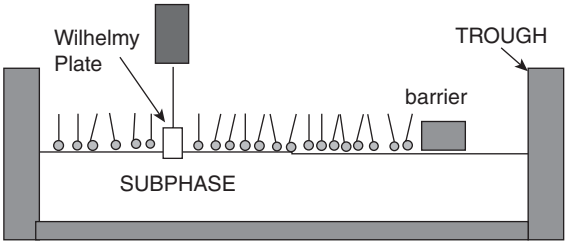

Figure 2.5 Cartoon of a Langmuir trough containing a water subphase and a surfactant spread at the air–water interface. The Wilhelmy plate is connected to an electronic balance. The movable barrier can be used to increase the surface concentration of the surfactant at the interface.

number of red blood cells, when spread out on the water of the trough, was twice the calculated surface area of the red blood cells. To explain their results, they concluded that the membrane is two lipid molecules thick and that the membrane is made of a bilayer.

The bilayer is composed of two layers of lipids arranged so that their hydrocarbon tails face one another to form an oily core held together by the hydrophobic effect, while their charged heads face the aqueous solutions on either side of the membrane. A phospholipid is an amphiphilic molecule that consists of a polar head-group and two non-polar fatty acid tails. The lipid bilayer forms a membrane matrix where other biomolecules such as proteins can be embedded.

The properties of the bilayer are determined by a number of factors, including the lipid composition, the lipid size and shape, and the temperature. The nature of the lipid head-groups and the length and degree of saturation of the hydrocarbon chains play an important role. The presence of a *cis* double bond in the carbon tail of a lipid produces a kink, which makes it more difficult to pack the tail with straight neighbors. Kinks effectively introduce disorder and lead to a more fluid behavior of the hydrocarbon region of the lipid bilayer. The more kinks there are, the greater the disorder and the more fluid the bilayer becomes.

The lipid bilayer acts as a barrier. The hydrophilic interfacial regions associate with water, while the inner hydrophobic core region contains essentially no water. Because of the oily nature of the bilayer, it is only permeable to small hydrophobic solutes. Hydrophilic molecules and ionic compounds have a very low permeability for transport through the lipid bilayer. Thus the lipid bilayer is permselective, allowing some molecules to pass through, but retaining others, thus regulating transport in to and out of the cell. The transport of species across the cell membrane can be by either passive diffusion, coupled diffusion, or active transport, which requires the expenditure of energy.

The cell membrane contains a wide variety of biological molecules, primarily proteins and lipids, which are involved in an array of cellular processes, such as transport, cell adhesion, and cell signaling. The plasma membrane also serves as the attachment point for both the intracellular cytoskeleton and the extracellular cell wall. The cell membrane surrounds the cytoplasm of the cell. In the plant cell, the cell wall forms the outermost boundary, but it plays mostly a mechanical support role rather than a role as a permselective boundary. The cell membrane anchors the cytoskeleton to provide shape to the cell, and in attaching to the extracellular matrix to help group cells together in the formation of tissues.

2.4.3
Solid-Supported Lipid Bilayers

Since a supported bilayer membrane was first used to investigate cellular immune responses, solid-supported lipid bilayers have been a widely studied topic of practical and scientific interest in recent years. Being well-defined models of biological membranes, phospholipid bilayers supported on solid substrates are important for their roles in fundamental biophysical research as well as in applications such

as biosensors. Supported lipid bilayer membranes have been formed onto glass, quartz, and silicon surfaces, onto non-functionalized metal surfaces, or onto self-assembled alkanethiol monolayers. Methods for bilayer formation have included the Langmuir–Blodgett technique, vesicle fusion onto the substrate, spontaneous thinning of lipid–decane mixtures, and adsorption of charged lipids onto oppositely charged surfaces. A bilayer deposited directly on silica, glass or gold is a model membrane with a lack of functional integrity, as shown in Figure 2.6. Similar to lipid bilayers, supported lipid bilayers can have domains that depend on the composition of the lipids in the bilayer.

To yield space for accommodating large integral trans-membrane proteins in the supported lipid bilayer and to give lateral mobility to membrane components, a flexible polymer layer, preferably a hydrogel, can be inserted between the solid substrate and the bilayer, as shown in Figure 2.7. In Figure 2.7, the supported lipid bilayer is on top of a water-soluble polyion. The polyion itself is supported on a self-assembled monolayer (SAM) of an alkanethiol on a gold substrate. Hydrated polymer layers, self-assembled monolayers, and supported polyelectrolyte films have served as soft cushions for lipid bilayers.

For insertion of large membrane proteins into the supported lipid bilayer, a thicker polymer cushion is needed to lift the lipid membrane away from the solid substrate, which can be achieved by employing the layer-by-layer polyion adsorption technique. Additional layers of positively charged poly(diallyldimethylammonium chloride) (PDDA) can be adsorbed by interleaving with a polyanion such as negatively charged polystyrene sulfonate (PSS). The technique is very suitable to prepare polymeric films with well-defined thickness and homogeneity better than 1 nm. The dominant interaction, electrostatic attraction of opposite charges, can be used to deposit a bilayer on top of the multilayer polymeric film. Figure 2.7 is an example of a supramolecular assembly that can be fabricated using different self-assembly techniques: chemisorption, physisorption, and vesicular deposition. Exposure of the system shown in Figures 2.6 and 2.7 to a solution of membrane proteins from (for example) a cellular source may cause the proteins to penetrate into the lipid bilayer. A variety of methods, such

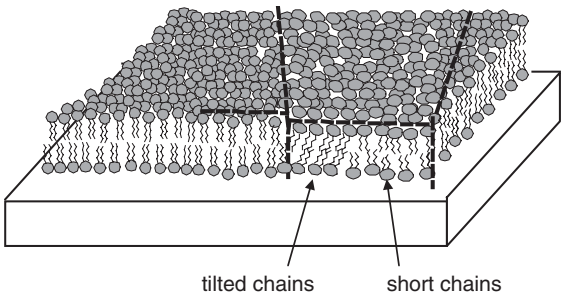

Figure 2.6 A bilayer supported on a solid support such as glass. The supported lipid bilayer is shown with two different domains. (Reproduced from Vidu *et al.* [1].)

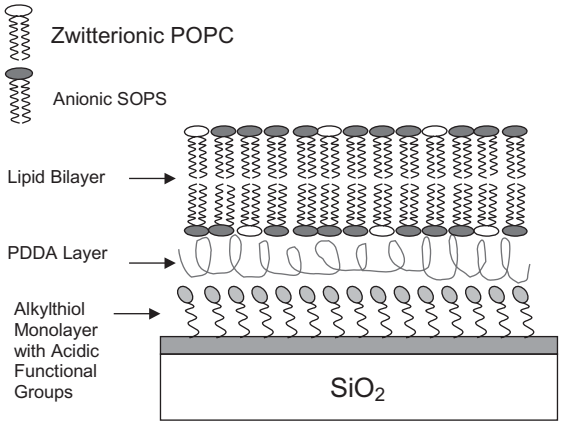

Figure 2.7 Schematic representation of the model membrane system. The alkylthiol 11-mercaptoundecanoic acid (MUA) layer is self-assembled on a gold surface. The negatively charged head-groups of MUA adsorb a cationic polymer (PDDA) layer. A lipid bilayer with negative charges is then deposited on the PDDA/MUA layer pair. (Reproduced from Zhang *et al.* [2].)

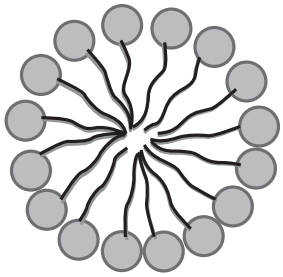

Figure 2.8 Schematic of a micelle in water.

as surface plasmon resonance, atomic force microscopy, cyclic voltammetry, and fluorescence, have been used to measure the uptake of proteins into supported lipid bilayers.

2.4.4 Micelles

A micelle is a colloidal self-assembled aggregate of surfactant molecules dispersed in a liquid and can form spontaneously from the monomer surfactant molecules if the surfactant concentration is sufficiently high. A micelle in an aqueous solution is a soft nanoparticle with the hydrophilic head-groups in contact with the surrounding water molecules and the hydrophobic tail regions sequestered inside the micelle center, as shown in Figure 2.8. The hydrophobic tails of the surfactant molecules have less contact with water when they are part of a micelle, and this

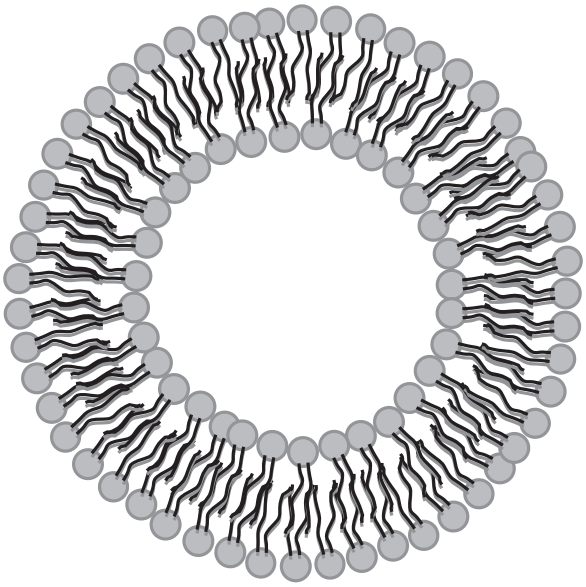

Figure 2.9 Diagram of a vesicle.

formation leads to a lowering of the free energy compared to the surfactant molecules being dispersed in the aqueous medium and interacting with water molecules.

In a hydrophobic medium, inverse micelles can form with the head-groups at the micelle center and the tails extending outward. Micelles are approximately spherical in shape depending on the solution conditions, such as surfactant concentration, solvent, temperature, pH, and ionic strength. Other micelle shapes include ellipsoids, cylinders, and bilayers. The shape and size of a micelle also depend on the composition and shape of the surfactant molecules besides the solution conditions. Micelles can form when the concentration of the surfactant is greater than the critical micelle concentration (CMC), and when the temperature of the system is greater than the critical micelle temperature, also known as the Kraft temperature.

Micelles composed of anionic or cationic surfactants have an electrostatic attraction to the counter-ions that surround the micelles in solution. The micelle charge affects the structure of the surrounding solvent at appreciable distances from the micelle. The distance of charge influence is known as the Debye distance, and it depends on the concentration of the ions in solution, the valences of the ions (but mainly the valence of the counter-ions), the dielectric constant, and the temperature. Ionic micelles can influence the properties of the colloidal mixture, including the electrical conductivity and the turbidity. The addition of salts to a colloidal solution of micelles decreases the strength of electrostatic interactions and can lead to the formation of larger ionic micelles.

2.4.5 Vesicles

A vesicle is an envelope of a lipid bilayer that forms a sac that encloses fluid and separates it from the continuous fluid. Vesicles can form naturally because of the self-assembly properties of lipid bilayers. A diagram of a vesicle is given in Figure 2.9.

Considerable research has been conducted on the use of lipid bilayers to understand the behavior of vesicles. The reason for this popularity is that the procedure of vesicle preparation is straightforward. Essentially, a phospholipid is first dissolved in a hydrophobic solvent with a high vapor pressure. The solution is then placed in a small flask or test tube and the container is rotated to allow the solution to wet the container walls. The solvent evaporates and the lipid deposits on the container wall. After all the solvent is evaporated, an aqueous medium is placed inside the container. At this point small vesicles can be produced by introducing an ultrasound tip and applying high-frequency mixing for a minute or so. Depending on the time and frequency of the ultrasound application, the vesicles will have a certain distribution of diameters. It is possible to produce vesicles with a diameter less than 1 μm. Alternatively, the container with the aqueous medium can be stored for several hours and over time the lipid on the walls becomes hydrated, separates from the container walls, and forms lipid bilayers that enclose to form vesicles. In the second process, very large vesicles (giant vesicles) are produced, with diameters in the order of from several to tens of micrometers. An image of a giant vesicle is shown in Figure 2.10.

Vesicles are used by the cell for organizing cellular substances. Vesicles can transport, store, and/or digest metabolites and waste products. They are involved in metabolism and enzyme storage, and can act as reaction chambers. Vesicles can fuse with the plasma membrane to release their contents outside of the cell. They can also fuse with the membranes of other organelles in the cell. Owing to transport mechanisms in the vesicle bilayer, the inside of the vesicle may be different from the cell interior.

There are a number of specialized vesicles in the plant cell. Lysosomes are vesicles that contain digestive enzymes used to break down substances in the cell. Food vacuoles are vesicles that contain mostly water and metabolic compounds. Food vacuoles fuse with lysosomes, which break down the components in the

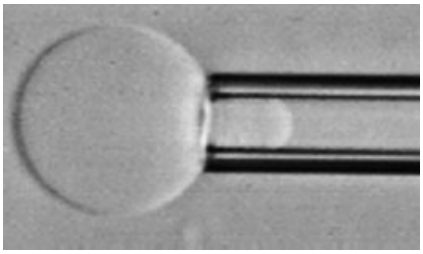

Figure 2.10 Giant vesicle with a diameter of 20 μm held (by suction) to a 7 μm micropipette. (Photo obtained courtesy of Dr. Henry Bouman.)

vacuole for further use in the cell. Lysosomes can also destroy defective or damaged organelles. The lysosomes fuse with the membrane of the defective organelle and then digest the organelle. Transport vesicles move molecules to different locations inside the cell. Secretory vesicles contain waste materials that need to be removed from the cell. The cellular control of the functions of the different types of vesicles is complex and not yet fully understood. The energy needed for these processes often comes from the metabolic reactions, which can also involve conversion of adenosine diphosphate (ADP) to adenosine triphosphate (ATP). ATP effectively stores chemical energy and can release it upon conversion to ADP. Study of cellular processes on the nanoscale seeks to understand the formation and functions of macromolecular assemblies and to couple this to what is known about the cell behavior on the molecular level.

2.5 Summary

Plant cell structures and functions are complex, and are determined on the nanoscale. Many of the structures can form by self-assembly. The understanding of how food processing changes these structures and their functions on the nanoscale is important to formulate new food products and to improve current processes. Nanoscience studies on how the processing of foods can cause favorable changes on the nanoscale can be explored to determine the optimum processing conditions to create value-added foods.

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