Polymers are long-chain molecules which consist of a repeating pattern of smaller subunits. Polymers are used extensively by living organisms and are essential for life. Synthetic polymers are manufactured by humans for use in a tremendous variety of materials.
Overview

Polymers are giant molecules, ranging in size from hundreds to tens of thousands of atoms. As the name indicates, a polymer consists of many repeating subunits called monomers.

A given polymer may consist of the same or several different monomers repeated over and over again within the molecule. In the case of different monomers, the patterned arrangement of the monomers may be orderly or random.

A monomer is a unique assemblage of atoms that are covalently bonded together by the sharing of electrons. Monomers abound in nature, especially within living organisms. The six principal atomic elements that comprise more than 98 percent of all living organisms are carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur. Both monomers and polymers are dominated by these six elements, in particular carbon and hydrogen. Some polymers are inorganic in that they are not associated with living organisms; examples include silicates and silica sand. Most polymers, however, are organic hydrocarbons, molecules consisting principally of carbon and hydrogen that are almost always found within living organisms.

Therefore, many monomers and polymers are manifestations of life. In living organisms, these molecules serve a variety of functions: information storage and transfer, catalysis of biochemical reactions, structural support, and energy storage. Examples of monomers found within living organisms include nucleotides, amino acids, and simple sugars (monosaccharides such as glucose). Examples of polymers formed within living organisms from these monomers include nucleic acids (DNA and RNA, formed from nucleotides, simple sugars, and phosphates), proteins (polypeptides, formed from amino acids), and carbohydrates (polysaccharides, formed from simple sugars).
Within the cells of living organisms, monomers are chemically bonded together with covalent bonds to produce polymers, a process that appropriately is called polymerization. The type of polymerization that occurs in living cells is dehydration linkage, in which the monomers are covalently bonded together with the loss of one water molecule for every link between every two consecutive monomers. Two monomers link to produce a dimer; a third monomer is linked to the first two to produce a trimer; a fourth monomer is linked to these three, producing a tetramer. The process will continue until it is signaled to stop or until the supply of monomers is exhausted. To illustrate the process of polymerization involving dehydration linkage, the synthesis of the beginning of a protein, a dipeptide, is illuminated as follows:

In this example, a hydroxide (-OH) group is lost from the carboxyl (-COOH) end of the first amino acid monomer, while a hydrogen (-H) atom is lost from the amino (-NH₂) end of the second amino acid monomer, thereby generating water as a by-product of the reaction. The same type of reaction would occur for the linkage of two monosaccharide (for example, glucose) monomers to produce a disaccharide (for example, maltose), the beginning of a carbohydrate such as starch or glycogen. When animals and other organisms digest food, they reverse the above process by adding water, a breakdown process called hydrolysis; polymers are broken down into their constituent monomers.

Polymers in Nature

In nature, food webs exist that continually produce and recycle monomers and polymers. The cycle begins with photoautotrophs, organisms such as plants, phytoplankton, and photobacteria that manufacture monomers and polymers from water, carbon dioxide, and minerals under the energetic stimulus of sunlight, a complex chemical process called photosynthesis. These organisms manufacture polymers such as DNA (deoxyribonucleic acid), RNA (ribonucleic acid), protein, and carbohydrates in order to construct the chemical reactions needed to sustain life. Other organisms, called heterotrophs, cannot conduct photosynthesis.

In the living cell, the polymer deoxyribonucleic acid (DNA) consists of billions of sequentially arranged nucleotide monomers: the sugar-linked nitrogen bases adenine (A), guanine (G), cytosine (C), and thymine (T). These four monomers are repeated in specific patterns favored by evolution to produce protein-encoding genes. The resulting genetic code determined by the arrangement of the four nucleotide monomers in DNA is used by the cell as a mold to synthesize the polymer RNA. RNA consists of the four monomers adenine (A), guanine (G), cytosine (C), and uracil (U). After DNA, the RNA is used as a mold for the construction of a protein polymer. The RNA nucleotide monomer sequence is in synchrony with its corresponding DNA nucleotide monomer sequence. Every three-consecutive-nucleotide monomer of the RNA polymer (AGC, CCU, GAG, and so on) encodes a specific amino acid in the amino acid sequence of the protein. A complex set of enzymes, also composed of proteins, called a ribosome reads the RNA polymer sequence of nucleotide monomers and links the appropriate amino acids together to produce a protein. Out of hundreds of types of amino acid monomers in nature, only around twenty types are found within the proteins of all living organisms.

Therefore, the cell is a nonstop factory that manufactures polymers. What is amazing is that the manufacture of polymers is conducted and controlled by other polymers. The living cell consists of polymers making polymers, a self-replicating phenomenon. Life itself is a continuous polymerization reaction, an endless crystallization of new giant molecules.

The polymeric nucleic acids DNA and RNA are respectively synthesized by two enzymes, which appropriately are named DNA polymerase and RNA polymerase, each of which is a protein polymer. DNA and RNA are information polymers within the living cell. Protein polymers, however, are catalytic enzymes that speed up or slow down chemical reactions within and between cells. Such enzymes include salivary amylase, a protein polymer that digests starch in the food that is eaten; insulin, a protein polymer that instructs liver cells to remove excess glucose from the bloodstream; and hemoglobin, a protein polymer that transports oxygen within the blood. There are thousands more such protein polymers within the human body alone.
Other protein polymers play a structural role inside and outside the cell. Microtubules and microfilaments are protein polymers that give a cell its shape. The proteins keratin and collagen are structural proteins that provide support and protection in the hair and skin.

**Polysaccharides** (carbohydrates or complex sugars such as glycogen and starch) are polymers that provide a food and energy reserve for the cell and the entire organism.

**Human Use of Polymers**

These natural polymers dominate our daily lives not only within our bodies but also within our industry and culture. Agriculture is geared toward food production, and food consists of the polymers that we must consume in order to survive. For example, meats, beans, and dairy products are rich in protein. Potatoes and rice are rich in carbohydrates. Furthermore, clothing and other textiles can be made from wool or cotton, polymers produced by sheep and the cotton plant, respectively. Gasoline is a natural hydrocarbon polymer that we use as fuel. Latex rubber is a natural polymer.

In the twentieth century, industrial chemists have succeeded in manufacturing synthetic polymers, durable polymers that are constructed artificially. Such synthetic polymers are used by virtually all Americans in some form every day, in plastics, Styrofoam, polyester clothing, paint, carpets, building materials, insulation, coatings, and other applications. The use of natural polymers with the present world population and current technological pace would very quickly devastate the environment and wildlife of earth. Therefore, synthetic polymers are an important step forward. The overuse of these materials, however, will produce more pollution and consume more petroleum. Fortunately, recyclable synthetic polymers are being developed.

Much of modern medicine is oriented toward relieving disease and infirmities at the molecular level. The fields of molecular biochemistry and genetics are geared toward mistakes and abnormalities in cellular polymers such as DNA and protein. Inherited diseases such as sickle-cell anemia and hemophilia are caused by defects in the structure and/or functioning of DNA and protein polymers. The same holds true for autoimmune diseases such as rheumatoid arthritis, in which the body's immune system attacks its own cells. Genetic engineering (for example, cloning) promises many breakthroughs in the study and developmental control of biological polymers, thus brightening the hopes of those who suffer from genetic disease.

Medical science also looks toward synthetic polymers as replacements for certain body organs and structures that have failed or become diseased. Such synthetic polymers and devices manufactured from them could be used to produce artificial skin, artificial joints, artificial hearts, replacements for internal body passageways, and so on. The synthesis of artificial polymers potentially offers some effective treatments for various disorders, improvements in the quality of human life, and extensions of the length of human life.

Synthetic polymers are so extensively used in Western society that they comprise half of the fifty most-produced chemicals manufactured in the United States. Millions of tons of synthetic polymers are manufactured, used, and disposed of every year. Most synthetic polymers are plastics, although fibers and rubber products are also prevalent. In most cases, synthetic polymers are derivatives of petroleum.

Like natural polymers, synthetic polymers are long chains of monomers. Some major monomers that are used in the manufacture of synthetic polymers include ethylene, styrene, vinyl chloride, and tetrafluoroethylene. When ethylene is polymerized, **polyethylene** is produced, for use in plastic items such as bags, containers, and toys:

In this example, the central double covalent bond of each ethylene is broken so that the two molecules can covalently bond together using spare electrons from the broken bond. More ethylene monomers can link to the di-ethylene dimer as the molecule polymerizes.

The other types of monomers polymerize in the same way. Styrene polymerizes to form polystyrene, an insulating material. Vinyl chloride polymerizes to form polyvinyl chloride, a major component of raincoats and floor tile. Tetrafluoroethylene polymerizes to form polytetrafluoroethylene, better known as Teflon. Teflon is a protective film coating for various items such as frying pans.
Context

Both natural and synthetic polymers are primarily organic hydrocarbons. There are also inorganic polymers, silicates and silica sand being prime examples found within the earth's crust.

The term "polymerization" is often used to describe crystal formation in liquids when liquid molecules freeze to form an ordered solid; however, this situation is a phase change for matter and does not involve covalent bonding like the covalent bonding that occurs between monomers.

In living organisms, polymers define and maintain life. The polymer DNA encodes the polymer RNA, which encodes the polymer protein. DNA and RNA are information polymers whose respective monomer sequences serve as programs for all aspects and activities of the organism. Proteins serve as catalysts for chemical reactions and as structural support for cells.

Another polymer, carbohydrate (for example, glycogen and starch), serves as a food/energy reserve for the living cell.

Synthetic polymers are extensions of natural polymers, since they have been developed by the incredibly complex arrangement of intelligent polymers that comprise the human brain.

Ultimately, polymers may be artificially produced that can mimic living polymers. Such a development would fall within the domain of artificial intelligence, the science that deals with intelligent computers and robotics.

In the meantime, medical science relies upon synthetic polymers and drugs in the treatment of patient maladies and the replacement of lost tissues and organs. One day, synthetic foods may be developed that would be more nutritious and that would pose less of a health risk than many natural foods. Artificial hearts, tracheae, joints, skin, and so on will help to improve the quality of human life, especially among the elderly as the populations of many countries, including the United States, grow progressively older.

In industry, synthetic polymers are being developed that are superior in quality and durability to natural polymers. For example, synthetic motor oils are superior to their natural hydrocarbon counterparts; although the synthetic oils are more expensive, they endure greater extremes of temperature and last longer. The other synthetic polymers are similar in their durability. Unfortunately, durability can have its drawbacks. Plastics are extremely difficult to decompose, consequently posing major problems for landfills and other forms of waste disposal.

Chemists actively are searching for new means of producing polymers having even higher quality and durability. They must find sources of monomers other than petroleum, and these monomers, when polymerized, must not adversely affect the environment. Furthermore, they must be recyclable.

Principal terms

**DEOXYRIBONUCLEIC ACID (DNA)**: a polymer of repeating nucleotides in two parallel chains that serves as the key information molecule for all living organisms

**HYDROCARBON**: an organic molecule whose principal elemental constituents are hydrogen and carbon; hydrocarbons are produced within living organisms

**MONOMER**: the simplest grouping of atoms that repeats itself in a polymer; examples include amino acids in protein polymers and glucose in starch polymers

**POLYESTER**: a synthetic hydrocarbon polymer of various forms that is used in the manufacture of clothing

**POLYMER**: a long-chain molecule of repeating monomer subunits that are arranged in a straight-chain or branching pattern

**POLYMERIZATION**: the process of polymer formation, when many monomer molecules are assembled and chemically linked, often by the removal of water
PROTEIN: a polypeptide; a polymer of amino acid monomers that catalyzes chemical reactions and provides structure within the cells of living organisms

STARCH: a carbohydrate, or polysaccharide; a common polymer of glucose monomers that is generated within plant cells as an energy storage reserve

Bibliography


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