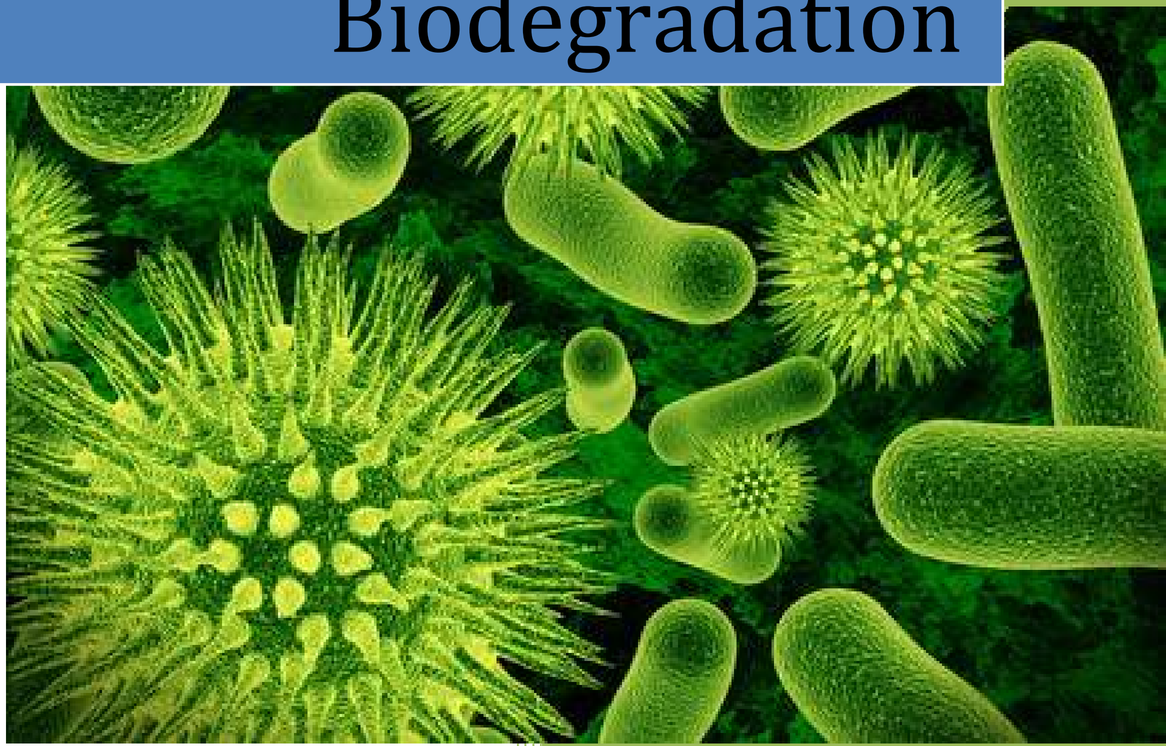
2010

Aerobic and Anaerobic Biodegradation



Danny Clark

ENSO Bottles LLC

06/29/2010

Aerobic and Anaerobic Biodegradation

A look into aerobic and anaerobic biodegradation

By

Danny Clark
ENSO Bottles, LLC
4710 E. Falcon Dr. Suite 220
Mesa, AZ 85215
866-936-3676

This document provides an explanation detailing the processes of aerobic and anaerobic biodegradation. It is intended for general audiences and will provide the reader with the necessary information to understand what is happening during the biodegradation process. For those interested in the biochemical processes of the microbial organisms this document will provide a high level explanation of the aerobic and anaerobic processes in the appendix.

Biodegradation

Biodegradation is the process by which organic substances (which are carbon based chains or rings also containing hydrogen and/or other elements) are broken down into smaller compounds by the enzymes produced by living microbial organisms. Biodegradable matter is generally organic material such as plant and animal matter and other substances originating from living organisms, or artificial materials that are similar enough to plant and animal matter to be put to use by microorganisms.

Micro-organisms transform the organic substance through **metabolic or enzymatic processes**. Biodegradation processes vary greatly, but frequently the final product of the degradation is carbon dioxide and/or methane and inert humus. Organic material can be degraded **aerobically**, with oxygen, or **anaerobically**, without oxygen.

> **Metabolic Process** is the set of chemical reactions that happen in living organisms to maintain life. These processes allow organisms to grow and reproduce, maintain their structures, and respond to their environments. Metabolism is usually divided into two categories. Catabolism breaks down organic matter, for example to harvest energy in cellular respiration. Anabolism uses energy to construct components of cells such as proteins and nucleic acids.
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> **Enzymatic Process** is the result of enzymes which are produced by micro-organisms to convert larger molecules into smaller molecules. Enzymes are proteins that catalyze (*i.e.*, increase the rates of) chemical reactions.

Some microorganisms have the astonishing, naturally occurring, microbial catabolic diversity to degrade, transform or accumulate a huge range of compounds including hydrocarbons (e.g. oil), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), pharmaceutical substances, radionuclides and metals.

Studies have shown that human influences such as pollution, agriculture and chemical applications can adversely affect the microbial diversity, and possibly above and below ground microbial ecosystems. There has been shown a decrease in bacterial biomass and activity in cultivated fields. Soil found to have a high diversity in bacteria and fungi results in higher soil quality and fertility.

Aerobic Biodegradation

Aerobic biodegradation is the breakdown of organic substances by microorganisms when oxygen is present. More specifically, it refers to occurring or living only in the presence of oxygen; therefore, the chemistry of the system, environment, or organism is characterized by oxidative conditions. Many organic substances are rapidly degraded under aerobic conditions by aerobic bacteria called aerobes.

Aerobic bacteria (aerobe) have an oxygen based metabolism. Aerobes, in a process known as cellular respiration, use oxygen to oxidize substrates (for example sugars and fats) in order to obtain energy.

Before cellular respiration begins, glucose molecules are broken down into two smaller molecules. This happens in the cytoplasm of the aerobes. The smaller molecules then enter a mitochondrion, where aerobic respiration takes place. Oxygen is used in the chemical reactions that break down the small molecules into water and carbon dioxide. The reactions also release energy.

Aerobic, unlike anaerobic digestion, does not produce the methane gases.

Anaerobic Biodegradation

Anaerobic digestion occurs when the anaerobic microbes are dominant over the aerobic microbes. Biodegradable waste in landfill degrades in the absence of oxygen through the process of anaerobic digestion. Paper and other materials that normally degrade in a few years degrade more slowly over longer periods of time. Biogas contains methane which has approximately 21 times the global warming potential of carbon dioxide. In a cradle to cradle approach this biogas is collected and used for eco-friendly power generation.

Anaerobic digestion is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen. It is widely used to treat wastewater sludge and biodegradable waste because it provides volume and mass reduction of the input material.

As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digestion is a renewable energy source because the process produces Methane and Carbon dioxide rich biogas suitable for energy production helping replace Fossil fuels. Also, the nutrient-rich solids left after digestion can be used as fertilizer.

The Anaerobic Process

The anaerobic biodegradation process begins with bacterial hydrolysis and fermentation of complex organic structures to smaller low-molecular-weight insoluble organic acids, such as carbohydrates (e.g. acetate). These smaller compounds can be used by some bacteria to be directly mineralized to CO2. Acetogenic bacteria then convert the low-molecular-weight organic acids (sugars and amino acids) into carbon dioxide, hydrogen , ammonia , and acetic acids. Methanogens finally are able to convert these products to methane and utilize hydrogen as an energy source.

There are a number of bacteria that are involved in the process of anaerobic digestion including acetic acid-forming bacteria and methane-forming bacteria. These bacteria feed upon the initial feedstock, which undergoes a number of different processes converting it to intermediate molecules including sugars, hydrogen & acetic acid before finally being converted to biogas.

Anaerobic Biodegradation Stages

There are four key biological and chemical stages of anaerobic digestion:

1. **Hydrolysis**
2. **Acidogenesis**
3. **Acetogenesis**
4. **Methanogenesis**

Hydrolysis

In most cases biomass is made up of large organic polymers. In order for the bacteria in anaerobic digesters to access the energy potential of the material, these chains must first be broken down into their smaller constituent parts. These constituent parts or monomers such as sugars are readily available by other bacteria. The process of breaking these chains and dissolving the smaller molecules into solution is called hydrolysis. Therefore hydrolysis of these high molecular weight polymeric components is the necessary first step in anaerobic digestion. Through Hydrolysis the complex organic molecules are broken down into simple sugars, amino acids, and Fatty acids.

Acetate and hydrogen produced in the first stages can be used directly by methanogens. Other molecules such as volatile fatty acids (VFA's) with a chain length that is greater than acetate must first be catabolised into compounds that can be directly utilized by methanogens.

Acidogenesis

The biological process of Acidogenesis is where there is further breakdown of the remaining components by acidogenic (fermentative) bacteria. Here VFAs are created along with ammonia, carbon dioxide and Hydrogen sulfide as well as other by-products. The process of acidogenesis is similar to the way that milk sours.

Acetogenesis

The third stage anaerobic digestion is Acetogenesis . Here simple molecules created through the acidogenesis phase are further digested by acetogens to produce largely acetic acid as well as carbon dioxide and hydrogen.

Methanogenesis

The terminal stage of anaerobic digestion is the biological process of Methanogenesis. Here methanogens utilize the intermediate products of the preceding stages and convert them into methane, carbon dioxide and water. It is these components that makes up the majority of the biogas emitted from the system.

Environmental Benefit of Anaerobic Biodegradation

Anaerobic digestion facilities have been recognized by the **United Nations Development Program** as one of the most useful decentralized sources of energy supply, as they are less capital intensive than large powerplants.

Utilizing anaerobic digestion technologies can help to reduce the emission of greenhouse gases in a number of key ways:

- Replacement of fossil fuels
- Reducing methane emission from landfills
- Displacing industrially-produced chemical fertilizers
- Reducing electrical grid transportation losses

Methane and power produced in anaerobic digestion facilities can be utilized to replace energy derived from fossil fuels, and hence reduce emissions of greenhouse gases. This is due to the fact that the carbon in biodegradable material is part of a Carbon cycle. The carbon released into the atmosphere from the combustion of biogas has been removed by plants in order for them to grow in the recent past. This can have occurred within the last decade, but more typically within the last growing season. If the plants are re-grown, taking the carbon out of the atmosphere once more, the system will be carbon neutral. This contrasts to carbon in fossil fuels that has been sequestered in the earth for many millions of years, the combustion of which increases the overall levels of carbon dioxide in the atmosphere.

Appendix A:
Are Plastics Biodegradable?

Yes, plastics can biodegrade through decomposition in the natural environment. Biodegradation of plastics can be achieved by enabling microorganisms in the environment to metabolize the molecular structure of plastic polymers resulting in biogases and inert humus material. They may be composed of either bioplastics, which are plastics whose components are derived from renewable raw materials, or petroleum-based plastics with the addition of a biodegradable additive. The use of certain types of additive compounds allows microbes to metabolize the plastic's polymer chain resulting in the assimilation of the plastic hydrocarbon into natural biogases and biomass.

There are some plastics, including some bio-plastics which use the term biodegradable to describe their product in very general and loose terms. These plastics require an initial mechanical or chemical processing phase in order to degrade the polymer into a state that will allow for microbial degradation. These conditions may or may not be naturally found in natural environments.

For example; a common bio-plastics which falls into this category is PLA (Poly-lactic Acid). This material has been marketed as biodegradable in compost environments. PLA requires an initial mechanical breakdown through a chemical process of exposing the polymer to high heat for a period of time (140 degrees for 10 days). This is not an environment that is readily found in nature, however, once PLA has been exposed to this chemical process the polymer has degraded into a state that will allow for the biodegradation of microbes in aerobic environments. This initial chemical breakdown requires that PLA be disposed of in very specific environments such as found in professional composting where the material can be manipulated to produce the desired results.

Another example; are plastics which utilize additive technologies which react to environmental conditions such as oxygen or UV. These additives which are technically identified as degradables sometimes claimed to be biodegradable. These types of additives are added into standard plastics and chemically bond to the polymer. When the additive chemically reacts to the environmental conditions whether that is oxygen, UV or some other reactant the chemical reaction causes the polymer to break at the point of connection. This results in the polymer becoming weak and brittle, eventually breaking down into smaller and smaller pieces of the original polymer. The thought is believed that the polymer will eventually become small enough for microbes to digest the material thus biodegrading the polymer into biogases and biomass. There has been no public data showing microbial biodegradation once this mechanical phase has been completed.

It is important to note that the customary disposal method should be taken into consideration when choosing the best environmental biodegradable plastic solution. If a bio-plastic, biodegradable plastic, or degradable plastic requires a specific environmental condition in order to initiate biodegradation it is extremely important that the biodegradable plastic packaging has the necessary means of making it into that required environment. The best environmental solution should not require special handling or processing of the disposed plastic material and will integrate into the existing disposal processes and methods, such as found in common waste management and recycling systems.

Plastics Degradation Standards

ASTM International, originally known as the American Society for Testing and Materials (ASTM), is one of the largest voluntary standards development organizations in the world and is a trusted source for technical standards for materials, products, systems, and services. Known for their high technical quality and market relevancy, ASTM International standards have an important role in the information infrastructure that guides design, manufacturing and trade in the global economy.

The ISO or International Organization for Standardization which is the world's largest developer and publisher of international standards is internationally recognized for its testing methods and standards for testing biodegradable plastics http://www.iso.org.

ASTM International has developed a set of specifications, test methods and guidelines for biodegradable plastics. Visit the ASTM website at http://www.astm.org.

Note: ASTM testing processes should be run according to the appropriate type of biodegradable plastic.

ASTM Plastics Degradation Standards

Definitions

- D883 Terminology Relating to Plastics

Specifications

- D6400 Standard Specification for Compostable Plastics

Test Methods

- D5210 Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge
- D5247 Standard Test Method for Determining the Aerobic Biodegradability of Degradable Plastics by Specific Microorganisms

- D5338 Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions
- D5511 Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions
- D5526 Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under Accelerated Landfill Conditions
- D7081 Standard Specification for Non-Floating Biodegradable Plastics in the Marine Environment

Guides

- D6002 Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics

Appendix B:
Bio-Chemistry of a Micro-Organism for Biodegradation

Although food contains energy, it is not in a form that can be used by cells. Cellular respiration changes food energy into a form all cells can use. This energy drives the life processes of almost all organisms on Earth.

Cellular respiration is the set of the metabolic reactions and processes that take place in organisms' cells to convert biochemical energy from nutrients into adenosine triphosphate (ATP), and then release waste products. The reactions involved in respiration are catabolic reactions that involve the oxidation of one molecule and the reduction of another.

Nutrients commonly used by animal and plant cells in respiration include glucose, amino acids and fatty acids, and a common oxidizing agent (electron acceptor) is molecular oxygen (O_2). Bacteria organisms may respire using a broad range of inorganic molecules as electron donors and acceptors, such as sulfur, metal ions, methane or hydrogen. Organisms that use oxygen as a final electron acceptor in respiration are described as aerobic, while those that do not are referred to as anaerobic.

When cells do not have enough oxygen for respiration, they use a process called fermentation to release some of the energy stored in glucose molecules. Like respiration, fermentation begins in the cytoplasm. Again, as the glucose molecules are broken down, energy is released. But the simple molecules from the breakdown of glucose do not move into the mitochondria. Instead, more chemical reactions occur in the cytoplasm. These reactions release some energy and produce wastes, i.e. methane.

The energy released in respiration is used to synthesize ATP to store this energy. The energy stored in ATP can then be used to drive processes requiring energy, including biosynthesis, locomotion or transportation of molecules across cell membranes. Because of its ubiquity in nature, ATP is also known as the "universal energy currency".

Electron transfer chain

The electron transfer chain, also called the electron transport chain, is a sequence of complexes found in the mitochondrial membrane that accept electrons from electron donors, shuttle these electrons across the mitochondrial membrane creating an electrical and chemical gradient, and, through the proton driven chemistry of the ATP synthase, generate adenosine triphosphate.

Electron Acceptor

Microorganisms such as bacteria obtain energy to grow by transferring electrons from an electron donor to an electron acceptor. An electron acceptor is a compound that receives or accepts an electron during cellular respiration.

The microorganism through its cellular machinery collects the energy for its use. The process starts with the transfer of an electron from an electron donor. During this process (**Electron Transport Chain**) the electron acceptor is reduced and the electron donor is oxidized.

Examples of acceptors include; oxygen, nitrate, iron, manganese, sulfate, carbon dioxide, or in some cases the chlorinated solvents.

These reactions are of interest not only because they allow organisms to obtain energy, but also because they are involved in the natural biodegradation of organic substances.

Electron Donor

Microorganisms, such as bacteria, obtain energy to grow by transferring electrons from an electron donor to an electron acceptor. An electron donor is a compound that gives up or donates an electron during cellular respiration, resulting in the release of energy.

The microorganism through its cellular machinery collects the energy for its use. The final result is the electron is donated to an electron acceptor. During this process (**Electron Transport Chain**) the electron donor is oxidized and the electron acceptor is reduced.

Petroleum hydrocarbons, less chlorinated solvents like vinyl chloride, soil organic matter, and reduced inorganic compounds are all compounds that can act as electron donors. These reactions are of interest not only because they allow organisms to obtain energy, but also because they are involved in the natural biodegradation of organic substances.

Note: Aerobic respiration produces 30 ATP compared to the 2 ATP yielded from anaerobic respiration per glucose molecule.

Adenosine-5'-triphosphate (**ATP**) is a multifunctional nucleotide, and is most important in cell biology as a coenzyme that is the key to intracellular energy transfer. In this role, ATP transports chemical energy within cells for metabolism. It is produced as an energy source during the processes of photosynthesis and cellular respiration and consumed by many enzymes and a multitude of cellular processes including biosynthetic reactions, motility and cell division. ATP is made from adenosine diphosphate (ADP) or adenosine monophosphate (AMP), and its use in metabolism converts it back into these precursors. ATP is therefore continuously recycled in organisms, with the human body turning over its own weight in ATP each day.

In signal transduction pathways, ATP is used as a substrate by kinases that phosphorylate proteins and lipids, as well as by adenylate cyclase, which uses ATP to produce the second messenger molecule cyclic AMP. The ratio between ATP and AMP is used as a way for a cell to sense how much energy is available and control the metabolic pathways that produce and consume ATP. Apart from its roles in energy metabolism and signaling, ATP is also incorporated into nucleic acids by polymerases in the processes of DNA replication and transcription.