Covenant University
4th Inaugural Lecture

MICROBIAL LIFE IN THE PRESENCE OF CARBON AND OXYGEN:

CONSEQUENCES FOR MAN

Louis Osayenum Egwari, (Ph.D)
Professor of Microbiology,
Department of Biological Sciences and Director,
Covenant University Centre for Research and Development

Corporate & Public Affairs, Covenant University,
Km. 10 Idiroko Road, Canaanland, P.M.B 1023, Ota, Ogun State, Nigeria
Tel: +234-039-602-002, 039-602-003, 039-602-004, 039-602-006.
Website: www.covenantuniversity.edu.ng

Covenant University Press,
Km. 10 Idiroko Road, Canaanland, P.M.B 1023, Ota, Ogun State, Nigeria

ISSN 2006...0327
Inaugural Lecture Series. Vol. 4, No. 1, February, 2014

Louis Osayenum Egwari, (Ph.D.)

Professor of Microbiology,

Department of Biological Sciences and Director,
Covenant University Centre for Research and Development

1. INTRODUCTION

Microorganisms have conquered all ecosystems traversing life in the presence or absence of oxygen, utilizing this element in diverse metabolic pathways in which carbon transformation ensures the perpetuity of life. But the Earth was once devoid of oxygen, yet these little creatures' adaptation to extremes of environmental stressors gives a glimpse to the origin of life on planet Earth. All oxidative processes require oxygen for efficient energy generation, yet oxygen kills; from singlet oxygen to oxygen metabolic bi-products including hydroxyl radicals and superoxide anions which are powerful oxidizing agents.

Living things metabolize, utilizing substrates and a network of electron system for this to occur. Substrates for the build up of complex polymers as in photosynthesis or the generation of energy from organic matter as in respiration comprise a carbon backbone with carbon dioxide being the simplest compound; an interesting fusion of two elements (carbon and oxygen) that have defined life. Be it a build-up process (anabolism) or a break down process (catabolism), there must be a regular and continuous flow of electrons. In this essence, oxygen provides the stream on which the delicate balance of life hinges.

Microorganisms, apart from providing us with the understanding of how life processes evolved, are actively involved in the dynamic transformation of matter. By implication, it might be inferred: 'no microorganism no life'. The two extremes of life that drive energy flow or the conversion of matter are biosynthesis and biodegradation; that is to say, if you eat you must defecate for healthy existence. How microorganisms function in bringing about this and the universal consequences of these microbial activities are examined in this lecture.

How it all began

Victoria Jaggard, a columnist of Astrophile, an online weekly column on cosmic objects, described the uniqueness of the Earth. She said this rocky planet has a special set of accessories that made it attractive to life and these include long lasting oceans, a protective magnetic shield and an oxygen-rich atmosphere. It also grew tectonic plates, which churn up new segments of crust in some places and shove older bits back down into the hot mantle, building mountains and shifting continents. This allowed the Earth to cool off as it aged and influenced the evolution of its billions of devoted inhabitants.

Scientists continue to unveil the mysteries of life on Earth. Emerging evidences have it that Earth life might have been influenced by planet Mars. It was supposed to be a chunk of rock that blasted off Mars and landed on the Earth, gave the Earth its physical nature, as it was originally covered in water and had little oxygen in its atmosphere. On the other hand, Mars had the right combination of dry land, oceans and oxygen in its atmosphere 3 billion years ago for life to form, as presented by Steven Benner at the Goldschmidt Geochemistry Conference on the 29th August, 2013.

Benner, who has dedicated his research to the study of the origin of life, says that in order for organic compounds to form life, they need to have oxygen and very specific minerals, especially boron and molybdenum. Without these minerals, putting organic compounds together usually results in tar. It was only when molybdenum became highly oxidized that it was able to influence how early life formed. According to Benner, this form of molybdenum could not have been available on Earth at the time life began, because 3 billion years ago, the surface of the Earth had little oxygen, but Mars did. Earth's planet-wide ocean apparently would have also prevented boron from accumulating and boron is essential for the formation of RNA, which was probably the very first genetic material formed (even before DNA). However, a meteorite found in Antarctica a few years ago, which was identified as being from Mars, was found to have boron in it. And Benner is of the opinion that the oxidized form of molybdenum was there too. These show the importance of oxygen in the formation of Earth and its inhabitants.

More recent findings by Sean Crowe, an assistant professor in the Department of Microbiology and Immunology and the Department of Earth, Ocean and Atmospheric Sciences at the University of British Columbia, and his colleagues at the University of Southern Denmark, and studies of researchers in South Africa indicate that oxygen appeared in the Earth atmosphere 700 million years earlier than thought. Scientists have thought photosynthesis first evolved in single-cell organisms about 2.7 billion years ago. Because oxygen is produced during photosynthesis, early photosynthetic organisms were thought to have given rise to the Great Oxygenation Event, also known as the Great Oxidation Event, about 2.3 billion years ago. The incidence was thought to be the first time the atmosphere began accumulating significant amounts of oxygen. That is significant because complex multicellular organisms such as humans require an oxygen-rich atmosphere to survive.

Microbial Activity in atmospheric gas formation

It has been demonstrated that interaction between ocean currents and bacteria led to the production of vast amounts of nitrogen gas in the Pacific Ocean. This takes place in one of the largest oxygen free water masses in the world; and the zones are expanding.

Three places in the world harbor extensive oxygen free water masses, called the Oxygen Minimum Zones. In these zones, microbes produce atmospheric nitrogen gas which accounts for almost 80% of Earth's atmosphere. Researchers from the University of Southern Denmark now report to have found the reason behind the huge nitrogen gas production in the three Minimum Oxygen Zones, located in the Pacific Ocean off Chile and Peru. The nitrogen gas is produced by a steady stream of bacteria that, when they feed, produce lots of nitrogen gas. An inter-university/research institute collaboration study (University of Southern Denmark, Aarhus University, Monterey Bay Aquarium Research Institute, USA, and Universidad de Concepcion, Chile), as reported by Dr. Loreto De Brabandere and Professor Bo Thamdrup of the Nordic Centre for Earth Evolution at the University of Southern Denmark, showed that the bacteria flow from the ocean current that comes from the Equator and heads towards the South Pole. On their way south, the bacteria rid the water of ammonia, which they eat and transform into nitrogen gas in the Oxygen Minimum Zone.

In the Western Pacific, off New Zealand, heavy and nutrient-rich water sinks below the water surface and begins to flow as an underwater current; first toward and along the Equator and then it changes course and heads south, when it approaches the coast of South America. During this long journey, oxygen disappears from the current's water, and off Peru and Chile the hungry bacteria go to work. The hungry bacteria in the ocean current from the Equator are called annamox bacteria and obtain energy to grow by allowing nitrate to react with ammonia and form nitrogen gas. Annamox bacteria and their impact on the global nitrogen cycle are enormous. Another group of bacteria, the denitrifying bacteria, produce nitrogen gas from nitrate and nitrite when combusting organic materials. However, the amount produced by these groups of bacteria is significantly less than that produced by annamox bacteria.

According to Bo Thamdrup, there are no indications that the ocean current may be disturbed by climatic change or other factors, and, thus, there will probably be no changes in its cargo of annamox bacteria. However, there are signs that the Oxygen Minimum Zones around the world are expanding, and this can lead to an increased production of atmospheric nitrogen. An increase in nitrogen gas emission leads to fewer algae in the water, and, thus there is less food for marine microorganisms. Ultimately, it means less food for the fish. Expanding Minimum Oxygen Zones may also weaken the ocean's capacity to absorb carbon dioxide, explains Loreto De Brabandere. "It gives more room for the nitrate-eating bacteria, and thus there are fewer nitrates available to marine plankton. Plankton is effective at absorbing CO_2, and if there is less plankton there will be less CO_2 absorbed."

2. THE OXYGEN CYCLE

Almost all living organisms need oxygen because it is essential in energy generation, and energy is required to do work. The oxygen cycle is the biogeochemical cycle that describes the movement of oxygen within its three main reservoirs: the atmosphere (air), the total content of biological matter within the biosphere (the global sum of all ecosystems), and the lithosphere (Earth's crust). Failures in the oxygen cycle within the hydrosphere (the combined mass of water found on, under, and over the surface of a planet) can result in the development of hypoxic zones. The main driving factor of the oxygen cycle is photosynthesis, which is responsible for the modern Earth's atmosphere and life on earth.

Three groups of photosynthetic organisms produce the bulk of atmospheric oxygen (plants, algae and cyanobacteria), the remainder comes from weathering. The cyanobacteria and algae are the source of much of the O_2 in the earth's atmosphere, considering their diverse ecology and especially in the marine habitats, which cover majority of the planet. Even though plants produce approximately ten times as much oxygen during the day as they consume at night, the night-time consumption of oxygen by plants can create low oxygen conditions in some water habitats. Oxygen in water is known as dissolved oxygen or OD. In nature, oxygen enters water when water runs over rocks and creates tremendous amounts of surface areas. The high surface area allows oxygen to transfer from the air into the water very quickly. When the water in the stream enters a pond, microorganisms in the pond begin to metabolize the organic matter, consuming oxygen in the process. This is another form of the oxygen cycle.

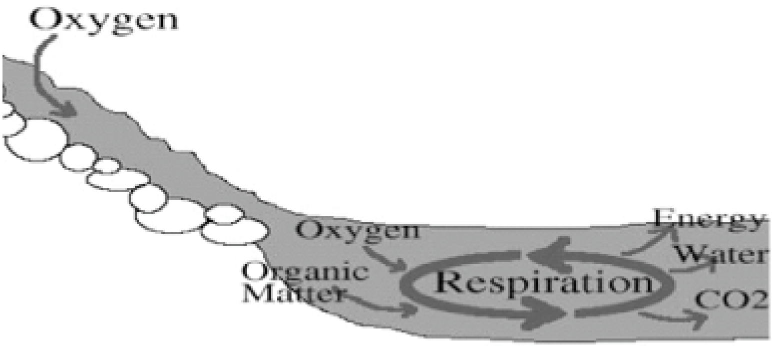


Figure 1: Oxygen cycle in aquatic environment. Source: Cloud and Gibor (1970)

Most aerobic organisms need oxygen produced during photosynthesis and in return make CO_2 available during respiration for photosynthetic activities. The main way free oxygen is lost from the atmosphere is through respiration and decay, mechanisms in which animal life and bacteria consume oxygen and release CO_2. The lithosphere also consumes free oxygen by chemical weathering such as the formation of iron oxide (rust). The presence of atmospheric oxygen has led to the formation of ozone (O_3) and the ozone layer within the stratosphere. The ozone layer is extremely important to modern life, as it absorbs harmful ultraviolet radiation.

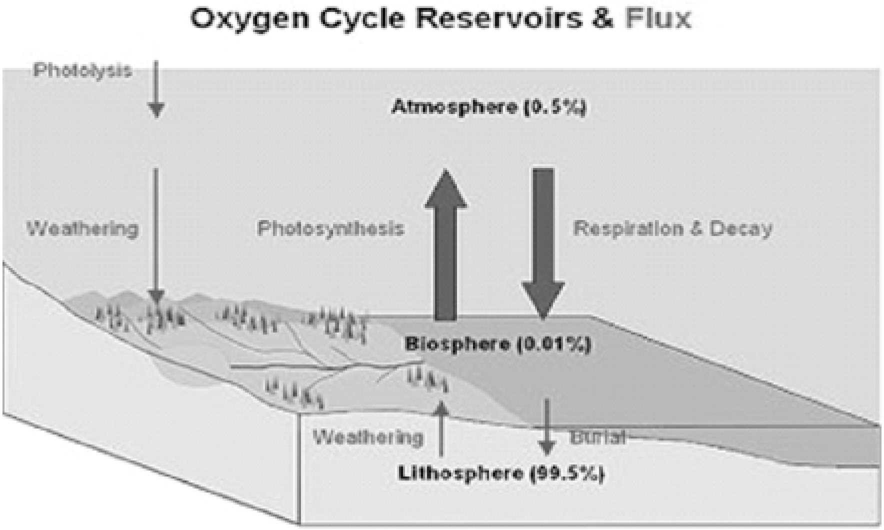


Figure 2: The global oxygen cycle.
Source: The Oxygen Cycle. http://water.me.vccs.edu/concepts/oxycycle.html

3. THE CARBON CYCLE

Microorganisms play a vital role in the functioning of an ecosystem. Carbon is fixed by the primary producers, which use light or chemically bound energy. Chemoheterotrophic bacteria and fungi serve as the main decomposers of organic matter. Some organisms such as protozoa serve as consumers by using bacteria and fungi as a food source.

Carbon can be present in reduced forms, such as methane (CH_4) and organic matter, and in more oxidized forms, such as carbon monoxide (CO) and carbon dioxide (CO_2). Reductants (e.g., hydrogen, which is a strong reductant) and oxidants (e.g., O_2) influence the course of biological and chemical reactions involving carbon. Hydrogen can be produced during organic matter degradation, especially under anaerobic conditions when fermentation occurs. If hydrogen and methane are generated, they can move from anaerobic to aerobic areas. This creates an opportunity for aerobic hydrogen and methane oxidizers to function.

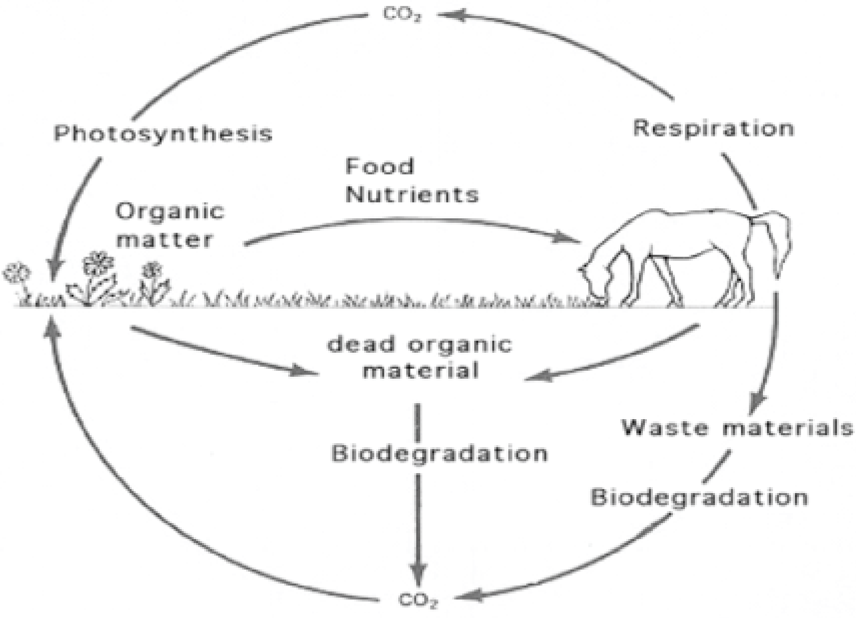


Figure 3. The Carbon Cycle. Organic matter (CH_2O) derived from photosynthesis (plants, algae and cyanobacteria) provides nutrition for heterotrophs (e.g. animals and associated bacteria), which convert it back to CO_2. Organic wastes, as well as dead organic matter in the soil and water, are ultimately broken down to CO_2 by microbial processes of biodegradation.

Sources: Todar K. (2013). http://textbookofbacteriology.net/themicrobialworld/environmental.htm, visited 04/10/2013.

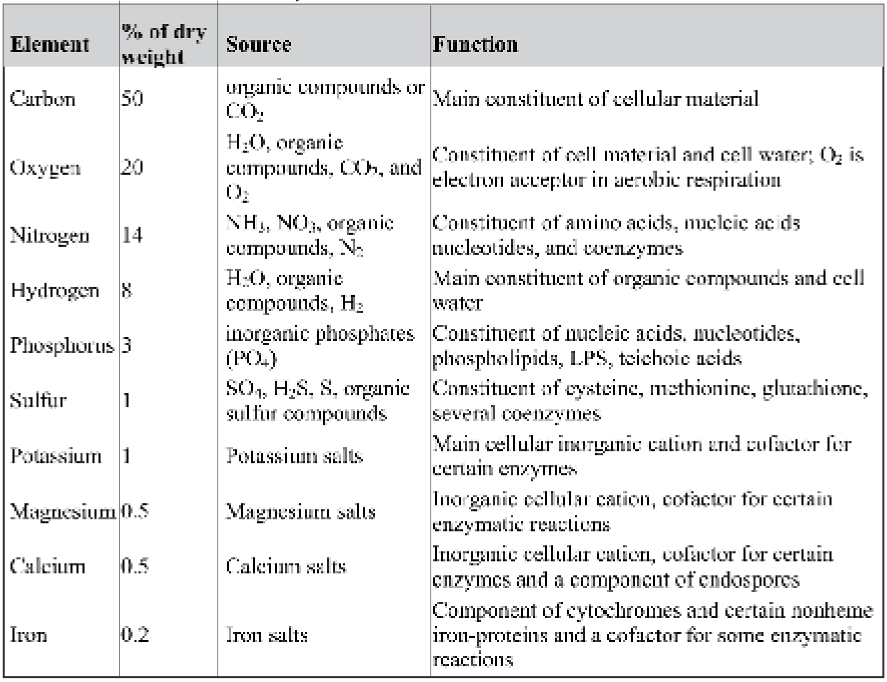
Methane levels in the atmosphere have been increasing approximately 1 % per year, from 0.7 to 1.6 to1.7 ppm (volume) in the last 300 years. If an aerobic water column is above the anaerobic zone where the methanogens are located, the methane can be oxidized before it reaches the atmosphere. In many situations, such as in rice paddles without an overlying aerobic water zone, the methane will be released directly to the atmosphere, thus contributing to global atmospheric methane increases. Ruminants can produce 200 to 400 litres of methane per day as a result of microbial activities in their gut. Other sources are coal mines, sewage treatment plants, landfills, and marshes. Anaerobic microorganisms in the gut of termites also can contribute to methane production.

Carbon fixation occurs through the activities of cyanobacteria and green algae, photosynthetic bacteria (e.g., *Chromatium* and *Chlorobium*), and aerobic chemolithoauthotrophs.

4. THE OXYGEN DILEMMA

Carbon (C), Hydrogen (H), Oxygen (O), Nitrogen (N) Phosphorous (P) and Sulfur (S) are elements that combine to form all the biochemicals and macromolecules that comprise living systems. With the exception of oxygen, these elements do not exist in the elemental form in a living system and neither is their uptake for cellular use. They are generally obtained and used in the oxidized form such as CO_2, H_2O, NO_4, PO_4, etc. Even oxygen may acquire another oxygen atom to become ozone which is released and accumulate in the atmosphere as the ozone layer, preventing the penetration to earth of harmful radioactive rays. Beyond this, many biochemical and catalytic reactions are oxidative requiring oxygen. In essence, the entire life on planet Earth requires oxygen combustion, respiration, biodegradation, corrosion and pathological processes. By implication, life will come to a standstill in the absence of oxygen. The only process that generates oxygen back into the atmosphere is photosynthesis. The oxygen-consuming activities are on the increase: increase in industrial activities, transportation demand, population increase, and a corresponding reduction in plant photosynthetic activity associated with deforestation and the loss of the carbon sink. This is the oxygen dilemma.

Table 1: Major elements, their sources and functions in cells.



Element	% of dry weight	Source	Function
Carbon	50	organic compounds or CO_2	Main constituent of cellular material
Oxygen	20	H_2O, organic compounds, CO_2, and O_2	Constituent of cell material and cell water; O_2 is electron acceptor in aerobic respiration
Nitrogen	14	NH_3, NO_3, organic compounds, N_2	Constituent of amino acids, nucleic acids nucleotides, and coenzymes
Hydrogen	8	H_2O, organic compounds, H_2	Main constituent of organic compounds and cell water
Phosphorus	3	inorganic phosphates (PO_4)	Constituent of nucleic acids, nucleotides, phospholipids, LPS, teichoic acids
Sulfur	1	SO_4, H_2S, S, organic sulfur compounds	Constituent of cysteine, methionine, glutathione, several coenzymes
Potassium	1	Potassium salts	Main cellular inorganic cation and cofactor for certain enzymes
Magnesium	0.5	Magnesium salts	Inorganic cellular cation, cofactor for certain enzymatic reactions
Calcium	0.5	Calcium salts	Inorganic cellular cation, cofactor for certain enzymes and a component of endospores
Iron	0.2	Iron salts	Component of cytochromes and certain nonheme iron-proteins and a cofactor for some enzymatic reactions

The table ignores the occurrence of "trace elements" in cells. **Trace elements** are metal ions required in cellular nutrition in such small amounts that it is difficult to determine or demonstrate their presence in cells. The usual metals that qualify as trace elements are Mn^{++}, Co^{++}, Zn^{++}, Cu^{++} and Mo^{++}. Trace elements are usually built into vitamins and enzymes. For example, vitamin B_{12} contains cobalt (Co^{++}) and the bacterial nitrogenase enzyme contains molybdenum (Mo^{++}).

Source: Todar (2013)

Microorganisms and oxygen

Oxygen requirement is used in classifying microorganisms. Those that grow in the presence of oxygen are called aerobes, those that grow only in the absence of oxygen are anaerobes and those that have adapted to life both in the presence and absence of oxygen are facultative anaerobes. In microbiology, we use this knowledge of their preference for oxygen to isolate them from clinical specimens. We also understand the nature of the diseases they cause based on this atmospheric classification. Here we see how oxygen determines the fate of certain microorganisms. We say there is no life without oxygen, yet oxygen kills some microorganisms. Beyond this, oxygen kills people, how?

> Oxygen kills time: procedures that fail due to excessive exposure to oxygen result in delayed reports.
>
> Oxygen kills confidence: one sees the organisms in the Gram stain, however, one fails to isolate it.
>
> Oxygen kills credibility: the physician knows the patient has an infection; however, the report says "no growth"!
>
> Oxygen kills budgets: one commits time and money to work-up a culture, however, one does not obtain the results one needed. Materials and time are thus wasted.
>
> Oxygen kills media: oxygen is the major cause of media deterioration. When exposed to oxygen during manufacturing and storage, media accumulate toxic products of oxidation that will inhibit the growth of many anaerobic pathogens.
>
> Oxygen kills people: when culture results are compromised by

> processing the specimen in the air and on oxidized media, the loser is the patient (Mike Cox, Anaerobe Systems, Morgan Hills, CA).

When oxygen kills anaerobes because they come in contact with it, it also affects us in many ways as given above. Oxygen, the giver of life, also is the taker of life; this also is a dilemma.

Products of oxygen metabolism

How does oxygen kill? The oxygen molecule (O_2), which is the ground state, is stable. The excited oxygen atom called singlet oxygen which can result from sonication or metabolic activities is a powerful oxidizing agent. Oxygen accepts electrons and is readily reduced because its two outer orbital electrons are unpaired. Many cell constituents including flavoproteins, and radiation promote oxygen reduction. The result is usually some combination of the reduction products superoxide radicals, hydrogen peroxide, and hydroxyl radical.

The oxygen reduction products are extremely toxic because they are powerful oxidizing agents and rapidly destroy cellular constituents. A microorganism must be able to protect itself against such oxygen products or it will be killed. Neutrophils and macrophages use these toxic oxygen products to destroy invading pathogens.

Many microorganisms possess enzymes that afford protection against toxic oxygen products. Obligate aerobes and facultative anaerobes usually contain the enzyme superoxide dismutase and catalase, which catalyze the destruction of superoxide radicals and hydrogen peroxide, respectively. Aerotolerant microorganisms may lack catalase but almost always have superoxide dismutase. The aerotolerant *Lactobacillus plantarum* uses manganous ions instead of superoxide dismutase to destroy the superoxide radical. All strict anaerobes lack both enzymes or have them in very low concentrations and, therefore, cannot tolerate oxygen.

5. CARBON: THE BACKBONE OF LIFE

Life depends on the existence of large molecules built around chains of carbon atoms. Carbon is one of the 118 elements on the Periodic Table of Elements. Carbon, Hydrogen, Nitrogen, Oxygen, Phosphorous and Sulfur, collectively known as the CHNOPS elements, make up 97 % of the human body; the rest of the human body is an eclectic mixture of minerals and metals. Humans depend on about 27 different elements, bacteria uses as few as 17 while viruses require even fewer.

The most important criterion of life, as well as being the most fundamental, is the ability to organize into repetitive structures at different orders of complexity both at molecular and cellular levels. Carbon has the unique ability amongst the elements to form molecular chains known as linear polymeric molecules (LPM), which are the key to replication and conservation of the creation instructions as found in DNA, RNA and peptides. Other elements that satisfy the LPM concept are silicon, boron and sulfur. Why then is carbon the backbone of life?

An LPM base must have at least three bonds, one to link to the base atom to its right and one to its left, forming the backbone; and another to the side group made up of co-atoms or molecules which then form the organic compound. It is possible to have more than three bonds, but for reasons of physical space, no more than four bonds on each base atom are realistically possible. Carbon is unique in that it forms only four bonds. Other candidates for the chain backbone (silicon, boron and sulfur) form inconsistent numbers of bonds from three to six, thus, making replication inconsistent and, therefore, unreliable.

Another unique factor that makes carbon a suitable life backbone is that its primary carbon to carbon bond is twice as strong as a silicon-silicon bond and also compared with its secondary link to the side group. This keeps the backbone of the structure in place, even under fluctuating temperatures; whilst at the same time allowing chemical reactions to occur on these secondary links. The carbon chain is able to link to a wide range of chemical elements and molecules. This, combined with carbon's chaining ability, enables the synthesis of vast range organic molecules that constitute metabolism in its simplest form. This has played important roles in economic activity, particularly in the manufacture of industrial chemicals and pharmaceuticals, all branches of medicine and in food production, both on the farm and in the factory.

Key carbon-based molecules in life processes include:

> Proteins, which are the building blocks from which the structure of living organisms is constructed. This includes all enzymes, which catalyze organic chemical reactions.
>
> Nucleic acids, which carry genetic information
>
> Carbohydrates, which store energy in a form that can be used by living cells
>
> Lipids, which store energy, but in a more concentrated form, and which may be stored for extended periods in the bodies of animals.

Contrasting silicon with carbon, silicon has four bonding sites and is below carbon on the periodic table. This means that silicon is very similar to carbon in its chemical characteristics. Man has, therefore, tried to build robotic life around silicon with the make-believe that a man-made machine built around the silicon crystal backbone will cross over from nonliving to living. Then it shall be the silicon based life, the robotic life or life on silicon chips.

Carbon compounds and interaction in nature

A carbon sink is anything that absorbs more carbon than it releases, whilst a carbon source is anything that releases more carbon than is absorbed. Forests, soils, oceans and the atmosphere all store carbon and this carbon moves between them in a continuous cycle. This constant movement of carbon means that forests act as sources or sinks at different times. Ecologists have long been interested in carbon. This interest stems from several reasons. Humans as well as plants and animals on Earth are made primarily of carbon. Nearly 50 % of their dry weight is carbon. Ecologists can learn much about ecosystems and what they do by constructing carbon budgets for energy (or energy budgets) from measurements of productivity, food chains, and nutrient cycling. Further, carbon in the form of carbon dioxide is a major greenhouse gas released to the atmosphere as a result of human activities. The continued release of greenhouse gases is raising the temperature of the earth, disrupting the climates we and our agricultural systems depend on, and raising the sea level. The concentration of CO_2 in the atmosphere has already increased by nearly 40 % since the start of the industrial revolution sometime around the middle of the 18th century and will continue to increase unless society eliminates the use of fossil fuels. The global carbon cycle involves the carbon in and exchanging between the earth's atmosphere, fossil fuels, the oceans, and the vegetation and soils of the earth's terrestrial ecosystems.

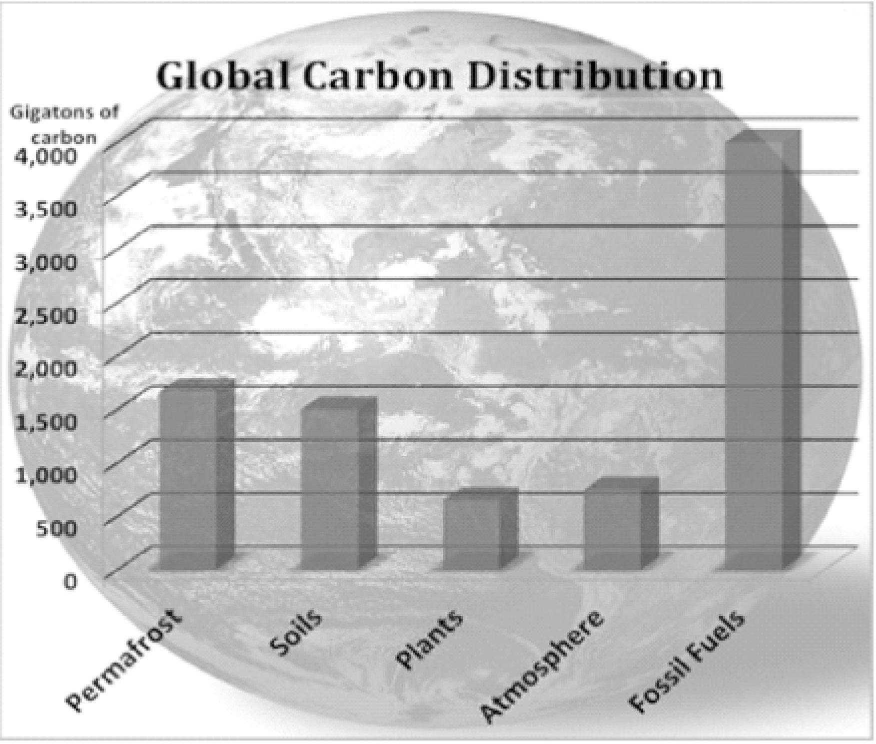


Figure 4: Produced by Gretchen Roecker/MEDILL. Data from Schaefer et al, National Snow and Ice Data Center (2011); Zimov et al, "Permafrost and the Global Carbon Budget" (Science, 2005)

Source: Medill Report Chicago: Story URL:
http://news.medill.northwestern.edu/chicago/news.aspx?id=194444
Story Retrieval Date: 10/2/2013 11:56:52 AM CST

Wood Hole Research Center studies show that for the years 1850 to 2005, about 156 PgC were released into the atmosphere as a result of changes in land use, 90 % from forests either blogged or converted to other uses, the rest largely from cultivation of prairie soils (one Pg [petagram] = 10^5 grams = one billion metric tons). The total loss of carbon from terrestrial ecosystems was 165 PgC, but about 15 PgC accumulated in wood products (e.g., buildings, furniture, paper, etc.). The net increment in these wood products is the difference between harvest (about 235 PgC) and oxidation of products (about 220 PgC) over this 155-year period. Conversion of natural ecosystems to croplands and pastures was responsible for net releases into the atmosphere of 107 and 21 PgC, respectively. The net effect of logging and re-growth was to release about 23 PgC. The annual rate at which carbon was released into the atmosphere generally increased over the period 1850 to 2005 as rates of deforestation increased.

For the period 1850 to 2005, a geochemical summary of the global carbon cycle is as follows (the terrestrial term having been determined indirectly by difference) (units are PgC):

Fossil fuel emission = Atmospheric increase + Oceanic uptake – Terrestrial net release

336 = 208 + 158 -30

The terrestrial net release may be the result of different processes, however:

Terrestrial net release = Release from land-use change – Accumulation in undisturbed ecosystems

30 = 155 - 125

The last term may be referred to as the residual carbon sink because it is determined by difference (it has not been observed).

Carbon's delicate balance and microbial activities

There are growing concerns on the fate of the vast carbon sink in permafrost in the Arctic system as the earth warms up. Permafrost, defined as ground frozen for at least two years, covers more than one-fifth of the northern hemisphere, an area more than six times the size of the United States that could shrink by 25 % due to warming by 2100. The mass of carbon trapped in its frozen organic matter which is more than 1,600 gigatons, is at least twice the amount in the Earth's atmosphere.

Microbes frozen for thousands of years can spring to life and digest the carbon to release heat-trapping gases into the atmosphere, amplifying warming and melting. According to Janet Janson, a microbial ecologist at the Lawrence Berkeley National Laboratory in Berkeley, Calif., “The concern is as the climate warms and the permafrost melts, that organic carbon becomes accessible to microorganisms”.

While the ocean holds the largest portion of Earth's carbon - about 40,000 gigatons - emissions from fossil fuel have driven atmospheric carbon up from about 560 gigatons in the preindustrial period to at least 750 gigatons today. That is still less than half the amount of carbon trapped in permafrost, but as the Arctic soils thaw and expose organic matter to microbes, the stored carbon could escape as greenhouse gases. Fossil fuels in this chart refer to energy sources such as coal still stored in the earth.

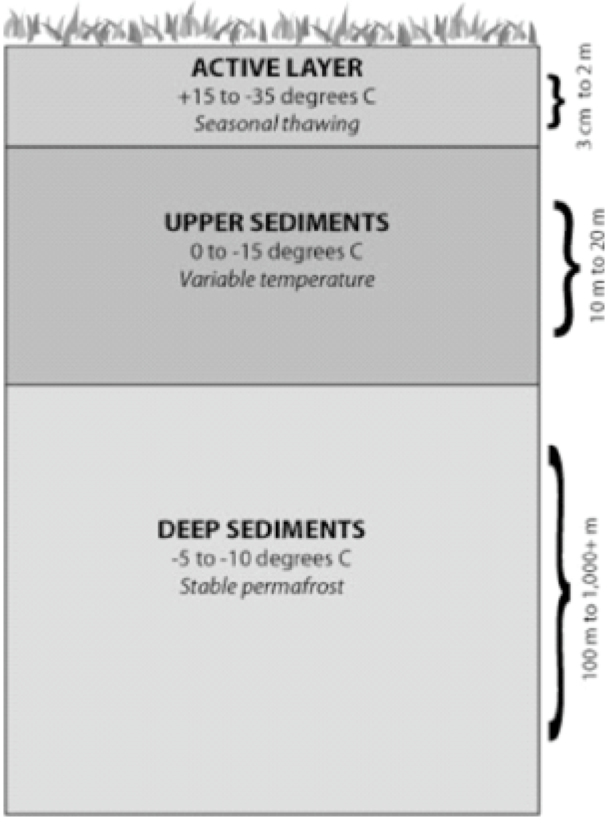


Figure 5: Stratification of carbon sink in Permafrost.

Source: Gretchen Roecker/MEDILL. Data from "Microbial Communities and Processes in Arctic Permafrost Environments,"

A permafrost primer: Plants at the surface take in carbon dioxide from the atmosphere, but freeze before being broken down. The uppermost "active layer" thaws each summer, allowing more plants to grow. Over hundreds to thousands of years, layers of carbon-rich material build up. Depth, temperature, moisture, nutrient content and other features vary greatly in the frozen ground at Earth's high latitudes, but permafrost is commonly defined as soil that remains at or below zero degrees C for at least two years.

The ability of microorganisms to degrade organic pollutants has been exploited in clean-up technology of contaminated environments. These bioremediation and biotransformation methods endeavour to harness the naturally occurring ability of microbial xenobiotic metabolism to degrade, transform or accumulate a huge range of compounds, including hydrocarbons (e.g., oil), polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHS), heterocyclic compounds such as pyridine or quinoline, pharmaceutical substances, radionuclides and metals.

Aromatic compounds are among the most recalcitrant of these pollutants, and lessons can be learned from the recent genomic studies of *Burkhoderia xenovorans* LB400 and *Rhodococcus* sp strain RHAI, two of the largest bacterial genomes completely sequenced to date (McLeod and Eltis, 2008). These studies have helped expand the understanding of bacterial catabolism, non-catabolic physiological adaptation to organic compounds, and the evolution of large bacterial genomes.

Anaerobic microbial mineralization of recalcitrant pollutants is of great environmental significance and it involves intriguing novel biochemical reactions. In particular, hydrocarbons and halogenated compounds have long been doubted to be degradable in the absence of oxygen, but the isolation of hitherto unknown anaerobic hydrocarbon-degrading and reductively dehalogenating bacteria during the last decades provided the ultimate proof for these processes in nature.

Many microorganisms affect anaerobic digestion, including acetic acid-forming bacteria (acetogens) and methane-forming archaea (methanogens). These organisms promote a number of chemical processes in converting the biomass to biogas (NNFCC 09-012). Gaseous oxygen is excluded from the reactions by physical containment. Anaerobes utilize electron acceptors from sources other than oxygen gas. These acceptors can be the organic material itself or may be supplied by inorganic oxides from within the input material. When the oxygen source in an anaerobic system is derived from the organic material itself, the intermediate and end products are primarily alcohols, aldehydes, and organic acids, plus carbon dioxide. In the presence of specialized methanogens, the intermediates are converted to the final end products of methane, carbon dioxide, and trace levels of hydrogen sulfide. In an anaerobic system, the majority of the chemical energy within the starting material is released by methanogenic bacteria as methane.

Implications for man

Anaerobic digestion is a collection of processes by which microorganisms break down biodegradable materials in the absence of oxygen. It is used as part of the process to treat biodegradable waste and sewage sludge. As part of an integrated waste management system, anaerobic digestion reduces the emission of landfill gas into the atmosphere. Anaerobic digesters can also be fed with purpose-grown energy crops, such as maize.

Anaerobic digestion is widely used as a source of renewable energy. The process produces a biogas, consisting of methane, carbon dioxide and traces of other contaminant gases. This biogas can be used directly as fuel, in combined heat and power gas engines or upgraded to natural gas-quality biomethane. The nutrient-rich digestate also produced can be used as fertilizer.

6. THE MARRIAGE BETWEEN CARBON AND OXYGEN

Photosynthesis and respiration

These twin processes define life on Earth. Photosynthesis is an energy conserving process through which carbon dioxide is reduced to organic compounds by plants, algae and photosynthesizing bacteria; oxygen is the scape goat. On the other hand, respiration ensures that the carbon dioxide concentration in the atmosphere required for photosynthetic activities is maintained by extracting oxygen from the atmosphere and paying a bride price of carbon dioxide. Perturbation of these processes may signify dire consequences.

Photosynthesis may be oxygenic or anoxygenic. Oxygenic photosynthesis occurs in plant, algae and cyanobacteria; water is the source of electron and oxygen is evolved. In anoxygenic photosynthesis, molecules other than water serve as the electron source; for example, hydrogen sulfide or organic substrates, oxygen is not evolved. Anoxygenic photosynthesis occurs in purple bacteria, green sulfur bacteria, green gliding bacteria and Gram positive bacteria; organisms that existed before the Great oxygenation Event.

The amount of carbon dioxide removed from the atmosphere each year by oxygenic photosynthesis is massive. It is estimated that photosynthetic organisms remove 1×10^{17} grams of carbon (C)/ year (Houghton and Woodwell, 1990). This is equivalent to 4×10^{18} KJ of free energy stored in reduced carbon, which is roughly 0.1 % of the visible radiant energy incident on the Earth/year. Each year the photosynthetically reduced carbon is oxidized, either by living organisms for their survival, or by combustion. The result is that more carbon dioxide is released into the atmosphere from the biota than is taken up by photosynthesis. The amount of carbon released by the biota is estimated to be 1-2 x 10^{15} grams of C/y. Added to this is carbon released by the burning of fossil fuels, which amounts to 5 x 10^{15} grams of C/y.

The oceans mitigate this increase by acting as a sink for atmospheric carbon dioxide. It is estimated that the oceans remove about 2 x 10^{15} grams of C/y from the atmosphere. This carbon is eventually stored on the ocean floor. Although these estimates of sources and sinks are uncertain, the net global carbon dioxide concentration is increasing. Direct measurements show that each year the atmospheric carbon content is currently increasing by about 3 x 10^{15} grams. Over the past 200 years, carbon dioxide in the atmosphere has increased from about 280 ppm to its current level of 360ppm.

Based on predicted fossil fuel use and land management, it is estimated that the amount of carbon dioxide in the atmosphere will reach 700ppm within the next century. The consequences of this rapid change in our atmosphere are unknown. Because carbon dioxide acts as a greenhouse gas, some climate models predict that the temperature of the earth's atmosphere may increase by 2-8° C. Such a large temperature increase would lead to significant changes in rainfall patterns. Little is known about the impact of such drastic atmospheric and climatic changes on plant communities and crops. Current research is directed at understanding the interaction between global climate change and photosynthetic organisms.

Fermentation

Fermentation is the enzymatic decomposition and utilization of foodstuff, particularly carbohydrates by microbes. Fermentation can also be defined as the anaerobic conversion of sugar to carbon dioxide and alcohol by yeast. A more expanded definition is the conversion of organic materials into relatively simple substances by microorganisms.

Microbial fermentation is the basis for the production of a wide range of pharmaceutical products, targeting practically any medical indication. Examples range from anti-cancer cytotoxic drugs and vaccines, anti-infectious diseases antibiotics and vaccines, to hormonal disorder therapy. The key elements of fermentation development are strain selection and optimization, media and process development, and finally, scale-up to maximize productivity. Downstream processing utilizes various technologies for extracting, concentrating and purifying the product from a dilute broth. Microbial fermentation as in the pharmaceutical industry is fast replacing mammalian cell culture for drug production for time and yield advantages which ultimately translate to cost.

Fermentation takes place throughout the gastrointestinal tract of all animals, but the intensity of fermentation depends on microbe numbers, which are generally highest in the large intestine. In all animals, two processes are attributed to the microbial flora of the large intestine; digestion and metabolism of carbohydrates not digested in the small intestine (e.g., cellulose, residual starch), and synthesis of vitamin K and certain B vitamins.

Cellulose is a common constituent in the diet of many animals, including man, but no mammalian cell is known to produce a cellulase. Several species of bacteria in the large bowel synthesize cellulases and digest cellulose. Importantly, the major end products of microbial digestion of cellulose and other carbohydrates are volatile fatty acids, lactic acid, methane, hydrogen and carbon dioxide. Fermentation is, thus, the major source of intestinal gas.

The synthesis of vitamin K by colonic bacteria provides a valuable supplement to dietary sources and makes clinical vitamin K deficiency rare. Similarly, the formation of B vitamins by the microbial flora in the large intestine is useful to many animals.

The fermentation technology had its origin from the first time someone made wine, which was perfected in the 1940's with the production of antibiotics, and is now the primary method of production in the biotechnology industry. Products such as acetone, ethyl alcohol, butyl alcohol, lactic acid, yogurt, cheese and pickles are produced through fermentation. The story below tells of the socio-political importance of microbial fermentation:

The making of Israel

In 1904, Chaim Weizmann was a chemistry professor at Manchester University in England, trying to make synthetic rubber. He was looking for a microbe that would produce the necessary butyl alcohol. Weizmann was a Russian-born Jew who was active in the Zionist movement which advocated the creation of a homeland for Jews in Palestine. During his stay in England, he became a leader of the international Zionist movement.

By 1914, Weizmann had isolated *Clostridium acetobutylicum*, a bacterium which used inexpensive starch to produce a high yield of butyl alcohol and acetone. However, World War I broke out in August 1914 and diverted attention away from synthetic rubber and toward gunpowder (cordite). As it turned out, the solvent for making nitrocellulose and thus cordite was acetone. Weizmann was instrumental in making available a source for the creation of this acetone.

Acetone had previously been made from calcium acetate imported from Germany. Since importation of the German calcium acetate was not possible and the United States did not have a large supply, Weizmann was recruited by Winston Churchill and the British Government to set up his microbial fermentation for the production of acetone from corn at the Nicholson Distillery in London.

After the war, when the British Prime Minister Llord George asked what honours Weizmann might want for his contributions, Weizmann answered, “There is only one thing I want, a national home for my people.” The result was the Balfour Declaration, which affirmed Britain's commitment to the establishment of a Jewish homeland.

Weizmann went on to make significant contributions to both microbiology and politics. In 1920, he began a long tenure as President of the World Zionist Organization. In 1948, when the United States was going to reverse its decision to support the independent state of Israel, Weizmann used his considerable negotiating skills to convince President Truman that the United States should affirm their support for the new country, leading to the founding of Israel. In 1949, he was elected the first president of Israel.

From microbiologist to President, Weizmann illustrates not only the persistence necessary in both research and politics, but the strange and interesting ways research and politics interact.

Corrosion

Bacterial or microbial corrosion, also known as microbial influenced corrosion (MIC), is corrosion caused or promoted by microorganisms, usually chemoautotrophs. It can apply to both metals and non-metallic materials, such as plastics and concrete (the nylon-eating and plastic eating bacteria).

In a humid environment and anoxic conditions, the corrosion of metals occurs as a result of a redox reaction that generates molecular hydrogen from ions, requiring bacteria, unlike anaerobic corrosion that occurs spontaneously. A base metal, such as iron (Fe), goes into aqueous solution as positively charged cations, Fe^{2+}. As the metal is oxidized under anaerobic conditions by protons of water, H^+ ions are reduced to form molecular H_2.

$$Fe + 2H^+ \qquad Fe^{2+} + H_2$$

$$Fe + 2H_2O \qquad Fe(OH)_2 + H_2$$

Usually, a film of molecular hydrogen forms on the metal. Sulfate-reducing bacteria, oxidize the molecular hydrogen to produce hydrogen sulfide (HS-) and water.

$$4H_2 + SO4^{2-} \qquad HS^- + 3H_2O + OH^-$$

The iron ions partly precipitate to form iron (II) sulfide. A reaction with water also occurs, producing iron hydroxide

$$Fe^{2+} + HS^- \qquad FeS + H^+$$

$$3Fe^{2+} + 6H_2O \qquad 3Fe(OH)_2 + 6H^+$$

The net equation comes to:

$$4Fe + SO4^{2-} + H+ + 3H_2O \qquad FeS + 3Fe(OH)_2 + OH^-$$

This form of corrosion by sulfate-reducing bacteria can, in this way, be far more harmful than anaerobic corrosion.

Aerobic bacteria involved in biogenic sulfide corrosion are *Acidithiobacillus thiooxidans*, *Thiobacillus thioparus*, and *Thiobacillus concretivorus*. Anaerobic sulfate-reducing bacteria involved in corrosion belong to the genera *Desulfovibrio* and *Desulfotomaculum*. Layers of anaerobic bacteria can exist in the inner parts of the corrosion deposits, while the outer parts are inhabited by aerobic bacteria. Bacterial corrosion may appear in the form of pitting corrosion; for example, in pipelines of the oil and gas industry. Anaerobic corrosion is evident as layers of metal sulfides and hydrogen sulfide smell. On cast iron, a graphite corrosion selective leaching may be the result, with iron being consumed by the bacteria, leaving graphite matrix with low mechanical strength in place.

Hydrocarbon utilizing microorganisms (HUM bugs), mostly

Cladosporum resinae and *Pseudomonas aeruginosa*, are commonly present in aviation fuel. They live in the water-fuel interface of the water droplets, form dark black/brown/green, gel-like mats, and cause microbial corrosion to plastic and other rubber parts of the aircraft fuel system by consuming them, and to the metal parts by means of their acidic metabolic products.

Pathology

Microorganisms that cause disease can be acquired endogenously or exogenously. In both cases, the host, parasite and the environment determine and contribute to the disease progression. The classical disease conditions such as tetanus, botulism, gas gangrene, salmonellosis, cholera, and tuberculosis are of the exogenous source. Most surgical wound infections are acquired from the patients' indigenous flora. It therefore follows that for disease to manifest, a pathogen must first gain entrance and localize in an ecological niche within the host where factors favorable for its survival, growth and proliferation exist. Consequently, anaerobic organisms must be situated in locations where there is debridement of tissues and vascular stasis.

At the beginning of the twentieth century, infectious diseases were the leading cause of death worldwide. Three diseases, pneumonia, diarrhea, and tuberculosis, were responsible for about 30 % of deaths in the United States (Cohen, 2000). Early infant and childhood mortality from infections contributed to a low average life expectancy. A number of developments, including improved nutrition, safer food and water supplies, improved hygiene and sanitation, the use of antimicrobial agents, and widespread immunizations against important infectious diseases, resulted in decreased host susceptibility and reductions in disease transmission.

By the late twentieth century, substantial reductions in child mortality had occurred in low-and middle-income countries. The decrease in the number of child deaths during 1960-1990 averaged 2.5 % per year and the risk of dying in the first 5 years of life dropped by half- a major achievement in child survival. During the period 1990-2001, mortality rates dropped an average of 1.1 % annually, mostly after the neonatal period.

During the period 2000-2003, four communicable diseases accounted for 54 % of childhood deaths worldwide. These are: pneumonia (19 %), diarrhea (18 %), malaria (8%), and neonatal sepsis or pneumonia (10 %) (Bryce, 2005). Under-nutrition is an underlying cause in more than half of all deaths in children younger than 5 years.

Disability-adjusted life years (DALYs) are a widely accepted metric for understanding the burden of disease. Lower respiratory tract infections are the leading cause of DALYs worldwide, accounting for 6.4 % of the total. HIV/AIDS is third on the list, accounting for 6.1 % while diarrheal diseases and malaria rank fifth and ninth, accounting for 4.2 % and 2.7 % of DALYs respectively. In high-income countries, lower respiratory infections are the fourth leading cause of death. No communicable disease is among the top ten leading causes of DALYs in high-income countries. In contrast, pneumonia, HIV/AIDS, diarrhea, tuberculosis, and malaria rank among the top ten causes of death and DALYs in low- and middle-income countries.

7. MY ACADEMIC ADVENTURE

In my formative academic career, I was privileged to draw from the experience, expertise and tutelage of the following erudite scholars and I owe then immense gratitude. Many of them do not have scholarly published works with me but their deposits shaped my academic inclination. I learned to dot the I's and cross the T's from Professor T. V. I. Akpata, patience in academic work from Professor Dosunmu Ogunbi, academic discipline from Professor Tolu Odugbemi, the act of abstract writing from Professor A. O. Coker, time prioritization from Professor O. O. Amund, research design, result analysis and manuscript preparation from Professor Vincent Olubunmi Rotimi. The act and essence of academic mentorship I acquired from Professor Fagbenro Beyioku and Professor U. E. Mendie. From Professor Akande, a surgeon, I learnt that exuding confidence in your mentee is the best way of mentorship. I want to say to them all, both those still with us and those that are resting in the bosom of God, thank you. Your little boy of many years past has come of age, and to you all I dedicate this inaugural lecture.

Professors Akpata and Amund are Environmental and Petroleum Microbiologists respectively. Professors Mendie and Beyioku Fagbenro are Pharmaceutical Microbiologist, and Medical Parasitologist respectively. Professor Ogunbi is a diarrhea expert, so also is Professor Odugbemi who is also an expert in sexually transmitted diseases. Professor Coker is called the Campylobacter man. I settled with Professor V. O. Rotimi, one of the pioneers and founding fathers of anaerobic bacteriology in Nigeria. I happen to belong to the second generation. If you know these people or you find them and search them out and return to look at me, you will find their deposits, that is, their academic genes in me.

In similitude, wherever you find the following persons you are certain to find deposits of the following in me in them: passion, timeliness, perseverance, commitment and drive for results. These include: Dr. Nneyi Nkiru Nwokoye, Dr. Francisca Obiageli Nwaokorie, Dr. Grace I. Olasehinde, Dr. Olayemi Ayepola, Samuel Eneojo Abah, Margaret I. Oniha, Isaac Ogunbunmi, amongst many others I have mentored over the years.

My academic journey has focused principally on the field of human infections caused by bacteria in locations such as female genitalia, Ear, Neck and Throat and the therapeutical efficacy of antibiotics. Milestones are the granting of patent rights to beverage drinks from pawpaw fruits, fermented rice products and culture media from crayfish and exoskeleton of shrimps and crabs. You may wish to visit my google scholar page, researchgate page, and Biological Science page on the Covenant University website for details of my profile. Read about me online or in the media for unfolding events.

8. EXPRESSION

I love this favourite writing which I captured in my book *Expression*. It reads:

Nothing is Barren

Give me an expression and I shall live
Speak of my existence when I am not yet visible
Confess my presence, spirit, soul and body
Make them believe that I am alive and well
Ask them to look and look with the eye of faith and they shall see me
Proclaim my existence with obsession
Feed it into their hearts
For when it is in their hearts
They shall see me with their eyes

This expression I call the great proclamation of faith!

Again, I want my work to come alive in the life of the people. That is why I give my thoughts practical expression.

9. CONCLUSION

Microbes are of immense importance to life. Only a small proportion causes disease and spoilage of articles, yet the economic, social and psychological burdens are unquantifiable. These are microbes that require organic matter as source of carbon for biosynthesis. Instead of fighting microbes with antibiotics and other harmful agents, let us dwell with them in harmony, for the sheep shall lie down with the lion and none shall be hurt. I think one way of achieving this is nutrient replacement technology (NRT). That is the synthesis of organic nutrient (a placebo) with high affinity for microbial cells. Our biotechnological drive should be in this direction. This will form the *New Science of Nutrobiotics*, the use of specific high affinity synthetic nutrients to satisfy microbial growth requirements. Then these little creatures that have sapped the global economy will go to sleep and we shall all proclaim now "*the giant slept*". The new cure is *Nutrobiotics* and not antibiotics and I recommend this as the future therapy to man's infectious predicaments. I also recommend the use of highly predictive synthetic organic nutrient probes for vaccination and therapeutics.

Welcome Nutrobiotics
Now Man can live happily with the Microorganisms

Vision 10:2022
Covenant University; 1 of 10 in 10
A Divine Verdict

10. ACKNOWLEDGMENTS

First, I want to return all the glory to my LORD Jesus Christ Who, by His infinite mercy and endless love, has sustained me and my family. He alone is behind the success story of my life, for He makes all things beautiful in His time. I thank You Jesus, especially for making today a reality in my life.

I want to deeply appreciate the Chancellor of Covenant University, Dr David O. Oyedepo, for the spiritual guidance, inspiration and love, from which I have drawn. Thank You for creating the platform on which I can express myself.

To the Pro-Chancellor, Pastor Abraham Ojeme, and the Vice-Chancellor, Prof. C. K. Ayo, for approving my inaugural lecture and all the support toward making this a success, I say thank you. To my Department and colleagues that have added value to my life one way or the other, thank you.

To all my students, past and present and for allowing your knowledge to enrich mine, God bless you. For my family members, friends and well-wishers that have taken time off to be part of this inaugural lecture, and all that have rendered support in one way or the other, I salute you.

To every one whose mentorship I have passed through, especially Professor V. O. Rotimi, thank you for giving me a shoulder.

Finally, to my wife Ejiro and our son Michael, the ones I love dearly, I love you with unquestionable love.

Thank you
God bless you
I love you all.

11. REFERENCES

Agren, G.I. 2010. Climate Change: Microbial mitigation. Nature Geoscience 3, 303-304.

Allison, S.D., Wallenstein, M.D., Bradford, M.A. 2010. Soil-carbon response to warming dependent on microbial physiology. Nature Geoscience 3, 336-340.

Anisimov, O.A., Nelson, F.E., Pavlov, A.V. 1999. Predictive scenarios of permafrost development under conditions of global climate change in the XXI century. Earth Cryology 3, 15-25.

Bryce, J., Boschi-Pinto, C., Shibuya, K. and Black, R. E, and the WHO Child Health Epidemiology Reference Group (2005). WHO estimates of the causes of death in children. *Lancet,* 365:1147-1152.

Case Christine (Microbiology Professor, Skyline College). Microbial fermentation: Changed the course of human history. http://www.accessexcellence.org/LC/SS/ferm_background.ph/ visited 09/10/2013

CBCnews.ca. Ancient oxygen discovery shakes up history of life on Earth. 09/10/2013

Cloud, P. and Gibor, A. 1970, The oxygen cycle, Scientific American, September, S. 110-123.

Cohen, M. L. (2000). Changing patterns of infectious disease. *Nature,* 406:762-767.

Davidson, E.A. and Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* 440, 165-173.

Det Norske Veritas (DNV). Problem and solution: Bacterial corrosion, www.dnv.com, visited 13/10/2013.

Egwari, L.O. and Rotimi, V.O. (1991). Survival of *Bacteroides species* in Amies transport medium stored at different temperatures. *Central Afr. J. Med.* 37(12) 415-419.

Egwari, L.O., Rotimi, V.O., Abudu, O.O. and Coker, A.O. (1995). A study of the anaerobic bacterial flora of the female genital tract in health and disease. *Central Afr. J. Med.*, 41(12):391-397.

Egwari, L.O., Rotimi, V.O. and Coker, A.O. (1996). Antibiotic susceptibility of clinical isolates of *Prevotella bivia* in Lagos, Nigeria. *J. Chemother.,* 8(1):47-51.

Egwari, L.O. and Mendie, U.E. (1996). Incidence of pyrexia in patients undergoing haemodialysis. *West Afr. J. Med.,* 15(2):101-106.

Egwari, L.O., Rotimi, V.O. and Coker, A.O. (2000). An experimental mouse model to study the pathogenicity of *Prevotella bivia* and investigation of possible virulence. *West Indian Med. J.,* 49: 20-26.

Egwari, L.O. and Otegbeye, F. (2000). Crayfish broth for bacterial culture. *East Afr. Med. J.,* 77: 36-39.

Egwari, L.O. and Aboaba, O.O. (2002). Environmental impact on the bacteriological quality of domestic water supplies in Lagos, Nigeria. *Revista de Saude Publica*, 36(3): 235-240.

Egwari, L.O., Iwuanyanwu, S., Ojelabi, C.I., Uzochukwu, O. and Effiok, W.W. (2005). Bacteriology of sachet water sold in Lagos, Nigeria. *East Afr. Med. J.*, 82(5): 235-240.

Egwari, L.O., Nwokoye, N.N., Obisesan, B., Coker, A.O., Nwaokorie, F.O. And Savage, K.O. (2008). Bacteriological and clinical evaluation of 12 cases of post-surgical sepsis of odontogenic tumours at a referral centre. *East Afr. Med.J.,* 85(6): 269-274.

Egwari, L.O., Obisesan, B. and Nwokoye, N.N. (2009).

Microbiological status of periodontal disease in Lagos, Nigeria. *West Indian Med. J.,* 58(4): 392-397.

Egwari, L.O., Buraimoh, M.O. and Nwokoye, N.N. (2011). Evaluation of two anaerobic systems for isolation of anaerobes. Microbiology Research, 2(e24): 88-90

Fasullo, J., Substitute Lectures for ATOC 3600: Principles of Climate, Lectures on the global oxygen cycle, http://paos.colorado.edu/~fasullo/pjw_class/oxygencycle.html

GHG. Carbon dioxide sinks-oceans. http://www.ghgonline.orgco2sinkocean.html

Global Ecology. The residual carbon sink. http://www.whrc.org/global/carbon/residual.html#sthash.NS2B3tmb.dpuf

Global Ecology. Carbon and changes in land use. http://www.whrc.org/global/carbon/landuse.html#sthash.IEis9Z5w.dpuf

IPCC. 2007. Climate Change 2007: Synthesis Report. Available at <http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_synthesis_report.htm>.

Jenkinson, D.S., Adams, D.E., Wild, A. 1991. Model estimates of CO2 emissions from soil in response to global warming. *Nature* 351, 304–306.

Jump up Jump up Steve Nadis, *The Cells That Rule the Seas*, Scientific American, Nov. 2003

Jump up Jump up Walker, J. C. G. (1980) The oxygen cycle in the natural environment and the biogeochemical cycles, Springer-Verlag, Berlin, Federal Republic of Germany (DEU)

Houghton, R. A. and Woodwell, G. M. (1989). Global climate change. Scientific America, 260:36-44.

Ivan Semeniuk (Science Reporter). New analysis on oxygen makes scientist rethink history of early life. Published September 25, 2013, The Globe and Mail online.

Linder Chris. Global Ecology: Understanding the global carbon cycle.http://www.whrc.org/global/carbon/index.html#sthash.GGmyObAe.dpuf

Luo, Y., Wan, S., Hui, D., Wallace, L.L. 2001. Acclimatization of soil respiration to warming in a tall grass prairie. *Nature* 413, 622-625.

McLeod, M. P. and Eltis, L.D. (2008). Genomic insights into the aerobic pathways for degradation of organic pollutants. Microbial Biodegradation: Genomics and Molecular Biology. Caister Academic Press, ISBN 978-1-904455-17-2

Medill Reports. Warming Arctic wakes up methane and microbes, study shows by Gretchen Roeker, November 08, 2011. http://news.medill.northwestern.edu/chicago/news.aspx?id=194444. Visited 02/10/2013.

Microbiology: The Beginning: Life-what is it made of? The importance of carbon. http://www.the guardians.com/Microbiology/gm_mbm13html

Mike Cox, Anaerobe Systems, Morgan Hills, CA

Morris, R.M., OXYSPHERE - A Beginners' Guide to the Biogeochemical Cycling of Atmospheric Oxygen, http://seis.natsci.csulb.edu/rmorris/oxy/Oxy.htm

PHYS.ORG. Unexpected interaction between ocean current and bacteria. Http://phys.orgnews/2013-09-unexpected-interaction-ocean-currents-bacteria.html

Rotimi, V. O., Egwari, L. and Akande, B. (1990). Acidity and intestinal bacteria: an *in vitro* assessment of the bactericidal activity of hydrochloric acid on intestinal pathogens. *Afr. J. Med. Med. Sci.,* 19: 275-280.

SAFC contract manufacturing services. Production of pharmaceutical compounds through microbial fermentation. Safcglobal.com, visited 09/10/2013

Schlesinger, W. H. and Andrews, J. A. (2000). Soil respiration and the global carbon cycle. *Biogeochemistry* 48, 7-20.

Schlesinger, W.H. and Lichter, J. (2001). Limited carbon storage in soil and litter of experimental *Verge* 8 Amendolara 8

Scott Sutherland (Reporter). New study supports idea that life on Earth originated on Mars. *Geekquinox*, Friday August 30, 2013.

Singh, B. K. Bardgett, R. D., Smith, P. and Reay, D. S. (2010). Microorganisms and climate change: terrestrial feedbacks and mitigation options. Nature Reviews/Microbiology; 8:779-790.

The Oxygen Cycle. htpp://water.me.vccs.edu/concepts/oxycycle.html. Visited 04/10/2013

Todar K. (2013) lecture notes on bacteriology University of Wisconsin, Madison, United State of America: Microbes and the cycles of elements of life. http://textbookofbacteriology.net/themicrobialworld/environmental.htm, visited 04/10/2013.

Victoria Jaggard (Reporter). Astrophile: Early Earth was a hot young smoker. *Astrophile*, Published 25 September, 2013.

Whitmarsh, J and Govindjee (2013). Photosynthesis and Photomorphogenesis. In Concepts in Photobiology, Edited by Singhal, C. G., Renger, S. K. Sopory, K. Irrgang and Govindjee. Nosa Publishers/New Delhi; and Kluver Academic/Dordrecht, pp.11-51.

Wikipedia. Bacterial anaerobic corrosion. http://en.wikipedia.org/w/index?title+Bacterial_anaerobic_corrosion/. Visited 03/10/2013