MATERIALS AND ENERGY DERIVED FROM CARBOHYDRATES : OPPORTUNITIES, CHALLENGES AND SUSTAINABILITY ASSESSMENT

Dr. S. SIVARAM
Director, National Chemical Laboratory, Pune

43 rd Founder Memorial Lecture

2007

SHRIRAM

Shriram Institute For Industrial Research
(A UNIT OF SHRIRAM SCIENTIFIC & INDUSTRIAL RESEARCH FOUNDATION)
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SRI- A model of self-sustainability in Research

Shriram Institute for Industrial Research (SRI) is a unique institute engaged in industrial research. The mandate of being self-sustainable, independent and unbiased are the main feature of its uniqueness. For over fifty years in Delhi, twenty five years in Bangalore and since last year in Gurgaon, SRI has been providing all the necessary technical support to the industry as well as the regulatory authorities and policy makers.

The major part of the activities include the product-driven research involving either the development of a new product or process or the modification of an existing product or process. The aim has always been to provide value addition to the user industries. Upscaling of technologies from lab scale to commercial scale is the specialty of the experts working in SRI. Validation of processes and methods, product differentiation and benchmarking, besides the quality standardisation are also being regularly undertaken by SRI.

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Like research, SRI has also established its name in the country in the field of analytical research, testing and inspection as per the most stringent norms and guidelines. SRI develops validated methods especially for microanalysis of residues in various food and farm products including herbal, functional foods, nutrients and actives in plants etc. SRI is known for structural elucidation of herbal products. Besides this, microbiological studies, bio-equivalence & bio-availability studies and bio-safety of GM crops & BT products etc are the thrust areas.

In the areas of environmental sciences, SRI provides services for environment monitoring, impact assessment and management plan, remedial measures, evaluation of pollution control devices and efficacy of the measure for pollution control.

Popularising the radiation processing using Cobalt 60 source for gamma radiation has been a big contribution of SRI to various industries especially those dealing in health care, spices, herbal and food processing.

BIO-DATA OF DR. S. SIVARAM

Dr. Swaminathan Sivaram, Director, National Chemical Laboratory, Pune, is a polymer chemist and science manager of distinction. After his Ph.D in Chemistry in1971 from Purdue University, USA, he joined University of Akron, USA. He joined IPCL before joining NCL in 1988 and became Director in 2002.

Dr. Sivaram is a recipient of Padma Shri; Vishwakarma Medal, INSA; Silver Medal of the Chemical Research Society of India; Millennium Medal of the Indian Science Congress Association; Distinguished Alumnus Award of IIT, Kanpur; Professor S.R. Palit Memorial Award of the Indian Association for Cultivation of Science; K.G. Naik Gold Medal of M.S. University, Baroda; FICCI Award in Physical Sciences and Om Prakash Bhasin Award.

Dr. Sivaram is an elected Fellow of Indian National Science Academy, Indian Academy of Sciences, National Academy of Sciences, Indian National Academy of Engineering and the Academy of Sciences for the Developing World. He is a Member of the Board of Governors of NIPER, Chandigarh, IISER, Pune and ICT, Mumbai and the Vice President of Indian Academy of Sciences, Bangalore.

Dr. Sivaram is a visiting Professor at the Univ. of Bordeaux, France, Free University of Berlin, Germany and University of Akron, USA. He has mentored 32 Ph.Ds; has 200 publications and over 90 patent applications. Dr. Sivaram has edited two books and is on the Editorial Board of several International journals.

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Abstract

Renewable resources and issues of sustainability are receiving increasing attention from academia, industry and Government. Carbohydrates or biomass produced by nature, through the process of photosynthesis, is believed to be the most abundant renewable resource on planet earth. Carbohydrates, in principle, have the potential to become the feedstock for producing materials and energy for human kind.

It is interesting to observe that until the beginning of the nineteenth century global economy was entirely based on carbohydrates. Only with the discovery of petroleum, world shifted progressively from carbohydrates to hydrocarbons.

With rising price of hydrocarbons, diminishing exploitable reserves, desire to reduce dependence on oil rich nations and insulate nation's economies from the vagaries of geopolitics, countries world over have been reexamining the imperatives of a shift from hydrocarbons to carbohydrates.

However, it must be recognized that there are considerable challenges in building a carbohydrate based economy. Some of these are technological, whereas, others relate to logistics, land use competition and sustainability. Use of renewable resources is not a synonym for a sustainable process.

Processes based on hydrocarbons can, often, be more sustainable than those based on biomass or other naturally derived resources. The process efficiencies realized from many petrochemical processes are often higher than those derived from biomass conversion processes.

Science and technology in today's world are replete with hype and buzzword. An average citizen, often, believes that all the ills of the world can be cured if only all our energy or material needs can be met by renewable bio-based resources. Technology constraints often force policy makers to take decisions which are expedient but not necessarily prudent in the context of long term sustainability. The current plethora of announcements around the world concerning bio-fuels is a case in point.

There are several nuances of the carbohydrate-based economy that needs attention. Unlike hydrocarbons, carbohydrates are not fungible, solids in nature and expensive to transport. Whereas, hydrocarbon conversion technologies can be easily transplanted in different geographies, carbohydrate conversion technologies require considerable adaptation depending on the geographic and climatic origins of the carbohydrates.

Lastly, if carbohydrate-based technologies have to realize their true potential in the development of a sustainable society, it is of utmost importance that Government policy makers, business decision makers as well technology generators are provided with the correct assessment tools to enable unbiased quantification of the contribution of carbohydrate based technologies to sustainability.

This lecture will address key opportunities, challenges and issues in the creation of a sustainable materials and energy platform based on carbohydrates.

It is indeed a great privilege and honor for me to deliver the Forty Third Shri Ram Founder Memorial Lecture, in memory of its founder, Lala Shri Ram Ji. Lala Shri Ram was a multi-faceted personality. He not only created wealth, but, distributed it through several institutions which bear his name today. As a great visionary he believed in the dictum that knowledge leads to progress of a society. He was also one of the earliest of our industrialists to believe that research and development is key to the sustenance and growth of productive enterprises. Shri Ram Research Institute for Industrial Research is a proud testimony to the vision of this great son of India.

Lala Shri Ram laid the foundation of the Indian chemical industry. He pioneered the production of vinyl chloride from acetylene, which in turn, was generated from hydrolysis of calcium carbide, a technology that had its origin in Germany during the Second World War. Thus, inadvertently, he laid the foundation of a chemical industry that was not dependent on fossil fuels. Whereas, this technology was progressively supplanted by an ethylene based route derived from cracking of petroleum hydrocarbons, world over, Shri Ram group companies still practice the acetylene based process in India. This is probably the only such process of its kind in the world in operation today. With the price of crude breaching the seventy dollar per barrel ceiling the world is today looking at options for producing energy, materials and chemicals from non-fossil resources. If Lala Shri Ram was with us today, I am sure, he would have certainly chuckled to see the world come a full circle in about fifty years.

Introduction

The greatest challenge to science and technology in the coming decades will be the search for sustainable sources of materials, energy, food and water supplies for all humanity. With global population likely to exceed ten billion by 2050 and the evolution of a society increasingly driven by consumption, man's insatiable need for food, water, energy and materials will bring severe distortions in the manner in which we manage and harvest biological (land and water) resources.

Humans have always influenced their habitats. Today's industrialized society is unique in the sense that access to biomass does not impose the ultimate limit ; humans have learned to decouple industrial activity from biological productivity by exploiting fossil fuel resources in the form of coal, gas and petroleum. Biomass, which was the predominant source of energy till the end of the 18th century has steadily declined and has been totally substituted by fossil fuels. Our material needs today are derived from petrochemicals. Even agriculture, the source of food and biomass, relies on fossil fuel and petroleum based chemicals. The impact of nitrogen fertilizers and chemical pesticides on agriculture hardly needs emphasis.

With the dawn of the twentieth century the impact of human society on nature escalated. Humans have already put close to half of the world's land surface to their service resulting in extensive land degradation and loss of biodiversity. Human activities have contributed to environmental effects, such as, stratospheric ozone depletion, global warming, climate changes, deforestation and eutrophication. At the same time it must be recognized that use of fossil fuels has saved large areas from deforestation. Yet, their use has had other environmental impacts. Therefore, today, there are attempts to reduce our dependence on fossil fuels and return to relying more on biomass and other renewable resources for our subsistence.

What then is the potential role of biomass (or carbohydrates) as a renewable resource in a future global industrial society? Can the future materials and energy needs of humankind be based on carbohydrate resources in a sustainable manner? What will be the implication of global shift to biomass on biodiversity, nature conservation and competition for land and other resources? We shall try and address some of these issues in the following paragraphs.

Biomass use for energy and materials

Energy and materials can be generated from several biomass resources. These are food crops, primary and secondary agricultural residues (grass, reeds, straw, husk, bagasse etc.) and energy crops (which are crops planted exclusively for energy and material purposes, e.g. rapeseed, jatropha, sugarcane).

The global production of fossil fuel (oil and coal) far exceeds biomass production in agriculture and forestry. The decoupling of energy use from biological productivity, which took place a century ago, has resulted in levels of energy consumption today that makes it rather improbable that global society can depend solely on biomass for energy. However, the situation is different when we look at materials. Presently, only 5-10% of total annual production of fossil fuels is used for the manufacture of materials, e.g. plastics, fibers, rubbers and bulk chemicals. Total cereal production of the world exceeds two billion tons, whereas, total plastic production does not exceed 0.2 billion ton.

Thus, carbohydrate resources, derived from forest residues, agricultural wastes and residues as well as non-food crops can play a major role as renewable feed stocks for the production of materials and chemicals in the future.

Global energy consumption is expected to more than double during the 21st century. If one has to restrict carbon dioxide emissions to 2 billion tons of carbon per year by 2100, the requirement of carbon - neutral energy resources will have to grow to levels several times the present fossil fuel use. There are several carbon-neutral energy resources, e.g., bio-energy, hydrogen, solar, wind, nuclear and fossil fuels with carbon capture and sequestration. Of this, bio-energy is relatively less expensive and ranks as one of few technological options capable of tackling climate change already today. However, it must be recognized that potential global biomass supply is low compared to the demand for carbon – neutral energy. Therefore, more expensive carbon-neutral energy sources will necessarily have to be deployed. The other reality is that energy is more expensive than food. Consequently, market forces will entice farmers to shift to crops for bio-energy applications. This, in turn, will push up land and food prices. This trend is already evident.

With 15-18% of corn grown in the US going for ethanol production, the price of corn in US is at a five year high. The farmers are shifting to corn at the cost of cotton and soybean. Soybean acreage is expected to decrease by 11% and cotton by 20%. Wheat prices are also at an all time high. In Mexico, the price of tortilla, a staple food, has tripled to $ 1.40/kg. The palm oil price in Malaysia has risen to unprecedented levels fuelled by the demand of the bio-diesel industry. The Malaysian government has imposed a moratorium on building new bio-diesel plants using palm oil. Surging demand for palm oil in Indonesia and Malaysia has already resulted in the destruction of vast swaths of rainforest. The US Government target of 132 billion liters of ethanol per year within ten years (20% of US gasoline consumption) is unlikely to be met solely by corn. Even if the entire production of corn by the US is converted to ethanol, it would result in only 100 billion liters of ethanol per year! Therefore, any large scale attempt to shift energy supply from fossil fuel to edible carbohydrates will push the prices of food up. Also, fewer carbohydrates entering the food cycle will push up animal feed prices resulting in more expensive poultry and meat. Lured by higher corn prices, several farmers in the US are giving crop rotation a skip, a decidedly unhealthy practice.

The socio-economic consequences of higher land values and higher food prices are complex and unpredictable. There is a risk of conversion of biodiversity rich ecosystems into monocultural biomass plantations and poor people might be evicted from their land. Biomass plantations, in principle, can be established in marginal or degraded land. However, left to market forces, use of prime cropland being used for bio-energy plantation cannot be prevented. Unlike developed economies, where the basket of food prices as a share of household expenditure is rather low, in emerging economies food often accounts for a very substantial part of the household expenditures. Therefore, an increase in food prices will have untold consequences. In a world with unequal economic development, a large bio-energy demand in one part of the world with strong paying capacities may adversely impact food security and availability in another part of the world. This will create ethical dilemma in the development of bio-energy strategies. Clearly, diverting food crops to energy application is not sustainable.

Transition from the current fossil fuel dependent global economy to more sustainable energy and material systems will not be easy or short. There are formidable technology challenges. Also such transitions do not occur by themselves. Every nation has to have a strategy and a vision for such a transition.

In spite of these challenges, shifting society's dependence away from petroleum to renewable biomass resources is generally viewed as an important contributor to the development of a sustainable society. Several industrial nations have set ambitious goals for replacement of fossil fuels as energy resources and material feed stocks.

Investment in R&D by government and energy related industries are an all time high. Royal Dutch Shell claims to have invested over US $ 1.25 billion in the last five years on renewable energy. Chevron has claimed an expenditure of US $ 200 million since 1999. It has committed US $ 25 million during the next five years for developing processes for the production of transportation fuels from renewable resources. Exxon – Mobil has committed a contribution of US $ 100 million to Stanford University over a period of ten years on research into carbon – neutral energy resources. BP claims on investment of

US $ 1 million on renewable energy. It has also announced setting up of a new Energy Biosciences Institute, a privately funded national laboratory, in the University of California, Berkeley Campus. It has set aside US $ 500 million over the next 10 years for this activity. Selected on a competitive basis, the new center will focus on bio-fuels. Dow Chemical Co., Chevron, Conoco-Phillips and Shell have joined University of Colorado, Colorado State University and National Renewable Energy Laboratory to set up a consortium called The Colorado Center for Bio-refining and Bio-fuels. However, these investments are still only a small drop in the ocean!

Total equity investments in bio-fuels were US $ 2.6 billion over the nine month period from the final quarter of 2005 to the third quarter of 2006. Currently, 10% of the global investment in energy is devoted to bio-fuels and is expected to increase to ~ 15% by 2010. Several nations have stepped up public funding to this area during the last few years.

Search for alternatives to fossil fuels has reached a point of inflection driven by several considerations, some technical and, others, economic and geopolitical. History of science and technology shows that when government and industry step up investment in R&D in a given area, solutions and options are bound to come. However, every solution must be evaluated based on rigorous and careful considerations of sustainability as well as impact assessment. Should edible crops be used for producing energy and materials? This is an easy option today because technology for such conversions is readily available. What are the prospects of second generation technology based on converting biomass from non food resources to bio-fuels and materials? What is the net energy balance in bio-fuels, i.e. the energy content of a fuel, minus the energy content of the petroleum and other fossil energy sources used over the fuels entire energy cycle? Utmost care must be taken while defining strategies for meeting the burgeoning fuels and materials needs of humankind. Long term sustainability issues must be assessed with a clear road map for transition. Short term solutions based on expediency or narrow stakeholder interests must be avoided. If these pitfalls are not avoided, this generation will be held responsible for causing greater damage to the global ecosystems, in many ways yet known, compared to what is attributed today as the ill effects of a fossil fuel based economy.

Technology imperatives in renewables – based energy and material resources

However, such large scale shift in resources will need total integration of innovative plant-resources and other bio-resources, synthesis of biomaterials and generation of bio-fuels and bio-power. This will require careful orchestration of many disciplines of science and technology, namely, plant biotechnology, fermentative and enzymatic processes, chemical catalysis, novel separation processes and chemical engineering.

Plant biotechnology will provide means to higher yield, altered stature, resilience to biotic and abiotic stress and desirable biomass composition. There is a need to double the biomass production with desirable physical and chemical traits from the present average biomass productivity of ~ 10 dry megagrams ha^{-1} $year^{-1}$. Doubling global productivity of biomass will depend on identifying the fundamental constraints on productivity and addressing those constraints with modern genomic tools. There is an urgent need to look for perennial plant resources as a source of feedstock for energy and materials.

The current efficiency of capture of light energy by the process of photosynthesis is less than 2%. Can engineered genes from plants and photosynthetic bacteria increase this efficiency? Are there possibilities to manipulate genes involved in nitrogen fixation to increase biomass content of plants? Can plants be engineered to grow at elevated rates under drought and high – and low – temperature stress? Can coregulation of lignin and cellulose biosynthesis be achieved in such a way that lignin content can be reduced and cellulose content increased?

In summary advances in plant sciences and genetics will be critical to the overall technology goals. The next generation of energy/material crops having desirable traits for use in modern bio-refinery operations will emerge from a fundamental understanding of this discipline of science.

These advances in plant science will have to be captured in subsequent bio-refinery operations. The term “bio-refinery” has been coined to describe future processing complexes that will use renewable agricultural residues, plant based carbohydrates and ligno-cellulosic materials as feed stocks to produce a wide range of chemicals, fuels and bio – based materials. By exploiting new chemical, biological and other related technologies they offer the promise of greatly expanding the use of renewable plant based materials as well as a means of transitioning to a more energy efficient and environmentally sustainable chemical and energy economy. Just like fossil resources based petroleum refineries, bio-refineries will need to exploit economies of scale and efficient use of all products and by-products. In a typical petroleum refinery, ~

5% of the output goes into the manufacture of chemicals and materials. The rest is consumed as energy and transportation fuels. This situation is not expected to be different for bio-refineries.

A bio-refinery will integrate both bioconversion and chemical technologies. Technologies that are especially critical are improved ligno-cellulosic fractionation and pretreatment methods, novel reactor designs for conversion of renewable feed stocks, improved catalysts, both chemical and biological, and application of novel separation processes.

Carbohydrates feed stocks, unlike hydrocarbons, are oxygenated materials. Conversion of hydrocarbons to oxygenated hydrocarbons as currently practiced is energy and capital intensive. Carbohydrates may offer more viable routes to alcohols, carboxylic acids and esters without resorting to an expensive oxygenation step.

In a “bio-refinery” operation, high value chemicals present in the biomass (such as fragrances, flavoring agents, high value chemicals, etc) will be first extracted. Thereafter, the carbohydrates will be transformed to building block chemicals containing two to six carbon atoms. Subsequently the residues will be used for the generation of bio-fuels. Streams that cannot be used for either chemical or bio-fuel conversions will be used to produce other forms of energy like steam, electricity or both.

An integrated bio-refinery is an approach that optimizes the use of biomass for the production of bio-fuels, bio-energy and bio-materials. It is necessary to develop a vision of such bio-refineries, depending upon the local sources of feed stocks. True economics will arise out of backward integration with agriculture and contract farming and forward integration with consumer needs. Whereas, agriculture, by definition is distributed, bio-refineries cannot be widely distributed. To gain economies of scale, they need to be large in size and centralized like the petroleum refineries of today.

Advanced bio-refineries are also likely to be capital intensive. It will leverage the accumulated body of knowledge in plant genetics, bio-chemistry, bio-technology, biomass conversion chemistry, and process engineering and separation technology. This will call for creative partnership between companies dealing with fuels and energy as well as chemicals and materials with enterprises managing agriculture, agro-marketing and food chain. Traditionally, these businesses have stayed far apart. Therefore, new synergies and culture will have to be evolved. Traditionally, national governments have had a greater say in agriculture, through direct subsidies, fiscal and tax incentives as well as political engagement. Chemicals, materials and fuel industry are largely deregulated and function in a market driven economy. The convergence of these two sectors can be expected to lead to conflicts and tension which needs to be effectively managed.

Several challenges must be met, as we progress on this road. The transition from a hydrocarbon based economy to a carbohydrate based one is not without its attendant risks. Unknown solutions in fundamental science as well as an understanding of the complex interplay between energy, materials, environment and society associated with a carbohydrate based economy must be managed with care and diligence. These challenges are daunting with no magic bullets in sight. Nevertheless, if we have to move towards a more sustainable planet earth, a shift to a renewable carbohydrate based economy from the present dependence on diminishing nonrenewable hydrocarbons, is not only essential but necessary.

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2003	Biotech Industries : Opportunities & Challenges	Dr. (Mrs.) Manju Sharma
2002	India's Medical Legacy	Prof. Dr. M.S. Valiathan
2001	A Reconstruction of the Human Genome and its Implications.	Dr. Eugene W. Myers
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