Materials and Energy Derived from Carbohydrates: Opportunities and Challenges

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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 per cent 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 rain-forest.

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.

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 biofuels 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.

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.

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, biochemistry, bio-technology, biomass conversion chemistry, 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.