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Global assessment of research and development for algae biofuel production and its potential role for sustainable development in developing countries

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HIGHLIGHTS

- Algae biofuels can make positive contribution to sustainable development in developing countries.
- Bibliometric and patent data indicate that many lack the human capital to develop their own algae industry.
- Large uncertainties make algae biofuels currently unsuitable as a priority for many developing countries.

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ABSTRACT

The possibility of economically deriving fuel from cultivating algae biomass is an attractive addition to the range of measures to relieve the current reliance on fossil fuels. Algae biofuels avoid some of the previous drawbacks associated with crop-based biofuels as the algae do not compete with food crops. The favourable growing conditions found in many developing countries has led to a great deal of speculation about their potentials for reducing oil imports, stimulating rural economies, and even tackling hunger and poverty. By reviewing the status of this technology we suggest that the large uncertainties make it currently unsuitable as a priority for many developing countries. Using bibliometric and patent data analysis, we indicate that many developing countries lack the human capital to develop their own algae industry or adequately prepare policies to support imported technology. Also, we discuss the potential of modern biotechnology, especially genetic modification (GM) to produce new algal strains that are easier to harvest and yield more oil. Controversy surrounding the use of GM and weak biosafety regulatory system represents a significant challenge to adoption of GM technology in developing countries. A range of policy measures are also suggested to ensure that future progress in algae biofuels can contribute to sustainable development.

1. Introduction

Global energy demand is increasing, driven by a mixture of sustained high consumption in the industrialised countries and rapid economic growth in developing countries such as India and China. Currently much of this demand is met by the combustion of fossil fuels with attendant problems such as supply insecurity, air pollution, price volatility, environmental degradation, and climate change. Here we assess the potential of a proposed next-generation technology derived from harvesting algae biomass to produce a liquid fuel that can partly contribute to alleviating some of these problems whilst simultaneously contributing to the sustainable development of developing countries.

In particular, we assess the current technical status of algae biofuel technology in relation to the production of the most common fuels (bioethanol, methanol and diesel) and describe the appropriateness of promoting the growth of an algae biofuel industry in developing countries. We also examine the potential role of modern biotechnology in improving commercial viability of algae biofuel. The size and location of algae research and development (R&D) activity is determined using international academic and patent publication records in order to estimate institutional capacity to benefit from the development of any potential industry. Given the uncertainty which still exists about the viability and suitability of this early-stage technology

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we avoid providing any new scenario estimates and instead conclude by offering suggestions on how policy can hope to overcome some of the obstacles identified.

2. Why the need for algae as alternative biofuels?

The most recent figures from the International Energy Agency (IEA) estimate that total energy consumption from all sources will rise from 406 quadrillion Btu in 2000 to 770 quadrillion Btu in 2035 (IEA, 2010a,2010b,2010c) (1 quadrillion Btu$=1\times10^{15}$ Btu$\approx1\times10^{9}$ GJ, which is approximately the amount of electricity consumed by Italy in 2008 (CIA, 2011)). The majority of this increase in demand is projected to come from the rapid growth of non-OECD countries such as India, China, and sub-Saharan Africa (IEA, 2010a,2010b,2010c).

Despite attempts made in recent years to improve energy efficiency and reduce demand, there will also be a significant albeit smaller increase in demand across the industrialised regions such as North America and Europe (IEA, 2010a,2010b,2010c). Currently, most of this energy demand is met by the combustion of fossil fuels such as petrol, coal, and natural gas (Fernandes et al., 2007). Against this backdrop of increasing energy use, all nations are facing a number of pressures to adapt their energy policies. The main drivers for this are: increasing crude oil prices, improving energy security, resource constraints, and the harmful effects of fossil fuel combustion on local air quality and the global climate (Bailis et al., 2005; IPCC, 2007; Wijffels and Barbosa, 2010; Yergin, 2006).

2.1. Food vs. fuel: 1st and 2nd generation biofuels

Liquid fuels obtained from the fermentation and esterification of crops such as maize, soy, and palm are already an established energy industry in the USA, Brazil, Argentina, and the European Union (Cheng and Timilsina, 2011). These fuels are collectively known as first generation biofuels, and can be further classified into bioethanol, biomethanol, or biodiesel. A serious criticism of these biofuels is that they can promote direct competition between the use of such crops for food and fuel, and indirect competition for agricultural land used to produce food crops which further led to the conversion of forested land for expanding crop production (Mueller et al., 2011a). Rathmann et al. (2010) provide a comprehensive overview of the arguments in relation to land use competition, with particular reference to the two largest biofuel producers, the USA and Brazil. Whilst accepting that agroenergy has led to a shift in food prices, they suggest that this may only be a short run effect and note studies where competition with food was not observed such as bioethanol from sugarcane in Brazil (Rathmann et al., 2010). However, the concerns about the possible economic, environmental, and social impacts of bioenergy-inspired land-use change prompted calls for more research in this area and a change in policies. The increased demand for crops from the fuel industry raised food prices globally leading up to 2008, particularly cereals, which reached their highest levels in 30 years (Mitchell, 2008). Although other factors such as droughts, increased food consumption, and commodity market speculation also contributed to the rises since 2002, the most important factor was the increase in biofuel production in the US and EU (Mitchell, 2008). This price spike had particularly negative implications for countries in sub-Saharan African countries where up to 80% of dietary energy comes from imported cereals (FAO, 2009).

This phenomenon has led to research into alternative sources and technologies. Efforts are now underway to develop methods for the sustainable use of the residual, non-food components of existing biomass sources such as the stems, leaves, and husks, along with the cultivation of non-food crops such as jatropha, mahua, tobacco seed and miscanthus (Mueller et al., 2011b). Whilst 'sustainability' and 'sustainable' are terms which have a wide variety of meanings (an issue which has led some to criticise their usefulness in guiding policy and action (Gatto, 1995; Rigby and Cáceres, 2001), we use the terms here in the classical sense of the concept of the triple-bottom-line, i.e., that the production process satisfies economic, environmental, and social sustainability objectives, as opposed to the traditional over-reliance on economic sustainability alone (Sims, 2003). With explicit reference to energy and agriculture then this requires a combination of sustainability concepts such as transitioning from the combustion of finite fossil fuels to renewable energy sources which have lower CO_2 emissions, and the cultivation of biomass which enhances environmental quality, is economically viable, and enhances the quality of life for farmers and society. Assessing the sustainability of any biofuel technology or project is another controversial area (Pope et al., 2004), with much of the focus being on appropriate life-cycle analysis (LCA), such as the energy/carbon balance at each stage of production and use, along with a greenhouse gas assessment (Lardon et al., 2009; Yee et al., 2009). However, this misses other important factors such as the effect on water and biodiversity or the impact on local employment and food security. More wide-ranging, integrated assessments have been developed by organisations such as the IEA Bioenergy initiative (Ackom et al., 2010; Eisentraut, 2010) and the Swiss-based Roundtable on Sustainable Biofuels (2010) to overcome these shortfalls. Broadly speaking then, a sustainable biofuel should be one that: (1) provides a net decrease in GHG emissions, (2) does not lead to local environmental degradation, (3) is comparable in price to existing fossil fuels, (4) contributes to local employment and economic development, and (5) avoids competition with food crops. Providing a practical but rigorous assessment tool to evaluate the sustainability of existing and next-generation biofuels is a difficult but necessary task.

Biofuels derived from sources such as non-food biomass and crops, termed 'second generation' biofuels, do not compete directly with arable land and so are thought to be sustainable (Chisti, 2007). They also have a lower environmental impact than first generation biofuels as they require less fertilizer, water, and pesticide inputs (Carriquiry et al., 2011; Sheehan, 1998). However, controversy also exists around possible land-use changes that have occurred in relation to the growth of these crops that undermines their sustainability (Havlık et al., 2010). In particular, commercial production of these second generation non-food crops such as jatropha tends to be grown on fertile land which places its production in direct competition for arable land used for food production (Achten et al., 2010). There are further indirect land-use changes that occur as new plantings of grain crops around the world are needed to make up the shortfall caused by the diversion of land and crops to energy, although the diffuse nature of these impacts makes their calculation subject to many arbitrary assumptions (Mathews and Tan, 2009).

The low conversion rates of plant-matter to fuel means that second generation biofuels have a limited ability to contribute to fulfilling energy demand, unless substantial areas are devoted to the cultivation of such crops. This is due to the greater difficulty in converting cellulose (the tough material that forms the cell walls of plants) to fuel compared with the comparatively simpler, direct fermentation process used to convert e.g. corn-starch to ethanol (Carriquiry et al., 2011). The dispersed nature of the raw material (either on marginal land or distributed across many farms), leading to de-centralised collection, poses another problem for economic production. However, the more fundamental challenge faced by all biofuels is that they are at an inherent disadvantage to conventional fuels in two important ways: (1) plant biomass has a