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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 lower energy density (e.g. 18.5 MJ/kg for miscanthus) compared with 'condensed' biomass such as coal (26 MJ/kg), and (2) energy must be invested in growing, harvesting, and processing plant biomass before a usable fuel can be produced whereas fossil fuels exist in a more readily combustible form (McKendry, 2002). This second issue of 'net energy balance' (the amount of biofuel energy output versus fossil fuel energy input) varies according to variables such as fuel type, plant species, production method etc. and whether biofuels make a positive contribution is still contested. For example, Pimentel and Patzek (2005) stated that bio-ethanol production using corn grain required 29% more fossil energy than the ethanol fuel produced whereas Hill et al. (2006) found that ethanol yields 25% more energy than the energy invested in its production. Resolving this debate is key to deciding whether biofuels can contribute to a sustainable energy system.

2.2. Algae biofuel—The 3rd generation

Partly due to some of the issues mentioned, growing interest is now focused on the development of third generation biofuels obtained from microalgae organisms. This is due to the potential for deriving higher productivity per unit area than previous feedstocks, in addition to avoiding direct competition with food crops (Wijffels and Barbosa, 2010). Nigam and Singh (2011) point to other third generation biofuels, derived from seaweed and microbes, but these are at an earlier stage of development and are not the focus here.

Microalgae are a collection of over 50,000 photosynthetic microorganisms that can grow rapidly and live in harsh conditions, due to their simple unicellular or multicellular structure. The biomass that is produced can be harvested from large open ponds or customised closed chambers called photobioreactors (PBR), dried, and then processed to produce bioethanol or biodiesel (Mata et al., 2010). Growth rates can be accelerated through careful species selection and growth conditions (e.g. amount of sunlight, water, and nutrients). Their simple cellular structure also makes them a promising candidate for genetic modification to further improve their yields (Mata et al., 2010). Algae with 30 wt% oil could produce 12,000 L ha^{-1} yr^{-1} compared with 5950 L ha^{-1} yr^{-1} from oil palm, and 1892 L ha^{-1} yr^{-1} from Jatropha (Schenk et al., 2008). In order to supply global oil demand it is estimated that 20.5% of arable land would be required to be converted to algae production although this could be reduced to zero if ponds and bio-reactors are situated on non-arable land (Schenk et al., 2008). Stephens et al. (2010b) estimates that devoting about 1.5–2.7% of all non-arable land to algae cultivation could satisfy global energy demand. However, it seems likely that any move away from fossil-derived oil will rely on a portfolio of technologies and substitutes, so the total hectarage required should be lower than this figure.

Growing microalgae could also be an important tool in combating global CO_2 emissions. This is due to their ability to act as a CO_2 fixation source as they convert CO_2 into biomass via photosynthesis at much higher rates than conventional biofuel crops (Kumar et al., 2010). Algae ponds could thus be sited close to CO_2 emissions plants where the flue gases would be pumped directly to the ponds to be used for the algal photosynthesis. Upon combustion of the resulting biofuel then the CO_2 emitted should equal the CO_2 fixed during growth with overall CO_2 neutrality, and avoided emissions from the fossil fuel that was not burned (Mata et al., 2010). The extent to which algae biofuel can help reduce carbon emissions and provide a positive net energy balance is still highly questionable, and resolving the matter is made more difficult by the scarcity of large scale plants in operation (Scott et al., 2010). In the review by Scott et al. (2010), they found that algae biodiesel provided only a marginal benefit in terms of energy balance and global warming reduction potential. They pointed out that this assessment was highly sensitive to choices at each stage of the production process such as algae strain, site location, cultivation technology, and refinery method. Laboratory experiments have yielded energy return on investment (EROI) of between 1.1:1 (Hirano et al., 1998) and 2.94:1 (Minowa et al., 1995) but an LCA of a virtual algae biofuel facility by Lardon et al. (2009) found that it was energetically unfavourable in 3 out of 4 scenarios. Further, positive energy balances were strongly related to the ability to extract energy from co-products such as biogas and combustion of the solid residue (Lardon et al., 2009). Hall et al. (2009) have estimated that only fuels which have an EROI greater than 3:1 provide the requisite net energy to provide a fuel source and maintain the transport infrastructure. This highlights the need for advances to be made in increasing the oil content of the algae and in reducing the inputs needed to grow the algae if the fuel is to be both environmentally and economically viable. Indeed, an LCA of electricity generation by coal/algae cofiring by Kadam (2002) suggested that it may even be better to combust the algae biomass rather than to extract the lipids.

The attributes of the different generations of biofuels from a sustainability perspective that includes their environmental, social, and economic impacts are compared in Table 1, along with fuel derived from crude oil. Whilst some of the issues raised in the table will be common to all of the technologies, it is suggested that if algae biofuels can improve their net energy balance along with their economic competitiveness then they can be more sustainable than the other options considered.

3. Environmental and social sustainability of algae biofuel in developing countries

3.1. Geography and growing conditions

The climatic zones suitable for the cultivation of algae are mostly located between 37° north and south latitude (Van Harmelen and Oonk, 2006). The potential yield of algae is highest in warm countries due to the presence of sunlight and optimum temperature which allows higher growth rates. The optimal temperature for growing many microalgae is between 20 and 30 °C (Demirbas and Fatih Demirbas, 2011). Outside this range, productivity may decline or the algae may die (Demirbas and Fatih Demirbas, 2011). Many developing countries particularly in South Asia, the Middle East and Africa are geographically situated in climatic zones favourable for large-scale cultivation of algae for biofuel production. A map showing the average annual temperature of the world is shown in Fig. 1. The map indicates the regions of the world where solar insolation, and by association, algae photosynthesis should be highest. The area within the box represents the approximate regions where algae biofuel production should be most favourable. However, careful consideration of local climate and growing conditions is needed, as desert regions such as the Sahara may not be suitable due to the low night-time temperatures that restrict algal growth (Van Harmelen and Oonk, 2006). The use of closed PBR systems for algal growth can avoid the effects of local climate by providing an optimum, controlled environment (Mata et al., 2010). However, the downside of PBR systems is the higher capital and energy costs involved reduces the carbon balance of the final fuel.

The development of algae-based biofuel may generate new employment opportunities. The choice of production facility (open pond or PBR) will be region/site specific, with different technical and labour skills required. Previous studies have shown that operation, maintenance, and biomass processing of open pond algae systems require lower-skilled workers and less financial investment than closed photobioreactors (Chisti, 2007, 2008;

Table 1
An overview of existing and proposed liquid fuels from a sustainability perspective.

	Current status	Environmental	Social	Economic
Fossil fuels *petrol, diesel, gas*	• well-developed global industry • key component in energy, transport, plastics, chemicals and agriculture industries • EROI (oil) 30:1 (Hall et al., 2009)	• fossil fuel combustion increases atmospheric CO_2 • local environmental degradation from oil drilling and spillages	• health impacts from exhaust (particulate matter) • major industry with range of skilled labour positions • industry investment in training and R&D • history of corruption and conflict (Humphreys et al., 2007)	• social cost of fuel subsidies (costly to public to subsidise industry) • oil deposits and companies can contribute significantly to public tax receipts and pension funds (Sachs, 2007)
1st Gen Biofuel *corn, sugar cane, soy, rapeseed*	• commercial product sold on forecourts • biodiesel from rapeseed (EU) or palm oil (Indonesia), bioethanol from sugar cane/ molasses (US, Brazil) • EROI (corn ethanol) 0.8–1.5:1 (Murphy et al., 2010)	• possible carbon neutrality (Wijffels and Barbosa, 2010). • reforestation potential on marginal lands (Muok, 2010) • land clearing and high carbon debt—at best 17 yrs for Brazilian sugarcane biofuel at worst 423 yrs for palm oil from Indonesia and Malaysia (Fargione et al., 2008) • monocultural farming leading to soil degradation	• meet rural energy needs and stimulate rural economic growth • increase value/income of marginal lands • increase employment, particularly in rural areas (Bailis et al., 2005) • weak land tenure security attract foreign investors leading to conflict (Arezki et al., 2012) • competition between crops for fuel and crops for food contributes to poverty and hunger (Bailis et al., 2005)	• high biofuel blends can require engine modifications • raised prices of food crops as growers switch to supplying bioethanol market. • artificially inflates prices for corn in US, reducing the need for government price support or export subsidies (De La Torre Ugarte, 2006)
2nd Gen Biofuel *forestry & farm tailings, grasses and shrubs*	• Pilot-plants: ∼0.1% of global biofuel supply (Mabee and Saddler, 2007) • Substantial plantation activity and process development occurring (Sims et al., 2010) • EROI (switchgrass)—5.4:1 (Schmer et al., 2008)	• waste/byproduct stream eliminates need for new inputs/resources e.g. bagasse and molasses from sugar production (Karezki and Kithyoma, 2006) • reduce waste production since recycling by-products • reduce carbon emissions (depending on land-use) • avoids land-use change and forest clearance • in practice, reports of expansion into forest areas (Muok, 2010) • biosecurity risk due to invasive species introduction (Ditomaso et al., 2010)	• avoids food vs fuel dilemma (if non-arable land is used). • distributed energy systems viable since waste streams are widely available especially for rural areas • meet rural energy needs and stimulate rural economic growth • no conflict with land tenure if only using residues • over-selling of yields creates frustration and distrust, e.g. Kenyan *jatropha* in (Hunsberger, 2010) • Initiatives in developing countries depend on donor funding for running costs	• infrastructural costs for e.g. biogas capture/distribution, but can be viable at small scale • dispersed nature of resource avoids monopoly • domestic source of fuel can avoid expensive imports
3rd Gen Biofuel *microbes, macroalgae and microalgae e.g. chlorella or spirulina,*	• commercial production of microalgae exists for nutrient industry but not profitable for biofuel • substantial lab-stage and pilot plant activity, esp. in USA and EU. (Singh and Gu, 2010) • EROI (bioreactor) 0.22:1 (Beal et al., 2011)	• high energy to land area ratio so avoids deforestation impacts and land tenure conflicts • potential escape of invasive algae impacting waterways (Ditomaso et al., 2010) • careful siting required to minimise water requirements	• don't require arable land so no conflict with food-crops • potential to provide a range of high-skill and low-skill jobs • can aid rural development	• major cost reductions need to be achieved by R&D of organisms and processing • large-scale production necessary to be economical • high plant costs and supporting infrastructure (e.g. roads, utilities)

FAO, 2008). Although PBR systems can result in higher algae productivity, in developing countries, open pond systems are favoured (Chisti, 2008; Norskera et al., 2011). This is because they are relatively cheap and the tropical climate found in many such countries is conducive for algae growth without the need for the expensive and technically demanding PBR systems (FAO, 2010).

3.2. Co-production to diversify benefits

Algae technology has enormous potential, not only for biofuel production, but also for the ability to co-produce proteins, carotenoids, carbohydrates, vitamins, amino acids, pigments and trace minerals, and other chemicals. Murakami et al. (1996)

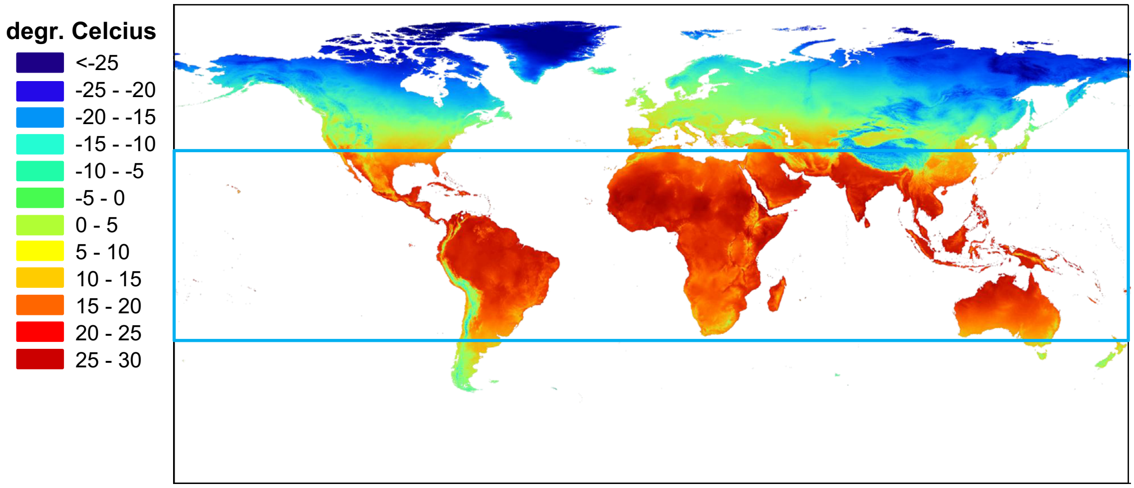

Fig. 1. A map of global mean annual surface temperatures taken from Van Harmelen and Oonk (2006). Regions within the blue box, with mean temperatures between 20 and 30 °C, are considered to have the most favourable climatic conditions for growing microalgae.

suggested that phytochemicals obtained from algae could even provide new avenues for tackling serious diseases such as cancer. Indeed the existing algae industry is based on the production of these nutrients and chemicals, and finding cheaper ways of producing them is the aim of much existing research (Spolaore et al., 2006). Whilst the US Aquatic Species Program report was optimistic about the possibility of algae biofuels to become economically viable on their own, provided that certain ambitious R&D goals were met (Sheehan, 1998; Chisti, 2007) argued that viewing algae production facilities as 'biorefineries' that produced a range of commercially valuable fuels (biodiesel and biogas) and products such as animal feed could improve their economics and usefulness. Reports by Wijffels and Barbosa (2010), Darzins et al. (2010), and Singh and Gu (2010) have all emphasised that algae-based biofuels could be economically feasible if co-production of chemicals, food and feed ingredients is considered, particularly in developing countries, but cautioned that current technology requires significant improvement. The predictions in Darzins et al. (2010) for example, are based on the assumption that algae have a lipid content of 50%, whereas current estimates range between 9.5 and 39.8% of biomass. They also point out that the market for algae co-products is small and may have little room for expansion.

3.3. *Resources vs. capability: The use of innovation indicators*

Whilst the favourable geography of many developing countries and the technical potential of the nascent algae biofuel industry is large, there are concerns about how developing countries can benefit equitably from its deployment. This concern arises from the disparity in educational, technical, political, and business expertise between the countries and organisations where the technology is being developed and the proposed locations for implementation. The development of any new industry requires not just the physical technology itself but also trained scientists, engineers, and technicians to run the plants, and skilled business people, financiers, and legislators to organise the formation and regulation of algae biofuel companies. Although crop-based biofuel industries and policies have been established since at least the 1980s in many developing countries, including sub-Saharan Africa (Amigun et al., 2008b; Ferguson, 2006; Jumbe et al., 2009), few accounts of current algae-based biofuel projects in developing countries were found in the existing literature. This agrees with a review in Singh and Gu (2010) that estimated that 78% of algae biofuel companies are based in the US, and a further 13% in Europe.

Here we use academic journal publications and patent data relating to algae biofuels to indicate the extent to which these capabilities exist in developing countries. Bibliometric approaches have been widely used in the field of innovation studies to assess the effect of R&D and policy measures, particularly in relation to emerging technologies (Meyer and Persson, 1998) and (Johnstone et al., 2010). Fig. 2 shows the major regions and countries in which academic research relating to algae biofuel is being undertaken. The data was obtained using a keyword search of the Thomson Web of Science™ science citation index expanded (SCIE) database between 1974 and 2010. The search term was 'fuel AND alga*' where the asterisk represents a search wild-card. The map shows that the Europe and the US are responsible for 70% of 566 publications relating to algae biofuel despite having relatively little land within the 'golden zone' of ideal growing conditions for algae. Emerging economic powers such as India and China are responsible for 5% and 3% of publications which is substantial but disproportionately small in relation to their population size. For the poorest nations in the African and South American continents then the tiny percentage of publications (2% each) being produced by institutions based here represents a challenge as they lack sufficient knowledge and human capital to exploit the possible opportunities of algae biofuel.

In terms of patent activity, a similar pattern is also seen, as shown in Fig. 3. The figure was obtained by querying the European Patent Office's esp@cenet database using the keywords 'biofuel', 'bioethanol', and 'biodiesel' and the Brazilian Patent Office (BPO) using the keywords 'biocombustive*', 'bioetanol', and 'biodiesel' between 1980 and 2009. Due to the greater technical immaturity of algae biofuel and the many non-fuel uses of algae (e.g. pollution treatment and nutrient production), 'algae' was not used in the keyword search in order to obtain a greater number of hits but restricted to energy uses. Whilst esp@cenet claims to have the most comprehensive collection of worldwide patents, it was noticed that despite the well-known biofuel industry in Brazil, very few patents were contained in the database. Therefore a separate search in Portuguese was conducted of the BPO database. The figure shows that similar to the location of academic publications, the majority of patent activity has occurred in the US (30%) and Europe (22%). Of the non-OECD countries, China and Brazil have some of the most developed biofuel industries, with 21% and 11%, respectively. Poorer developing countries have produced very few patents, again indicating the lack of indigenous capability for managing the developing algae biofuel industry.

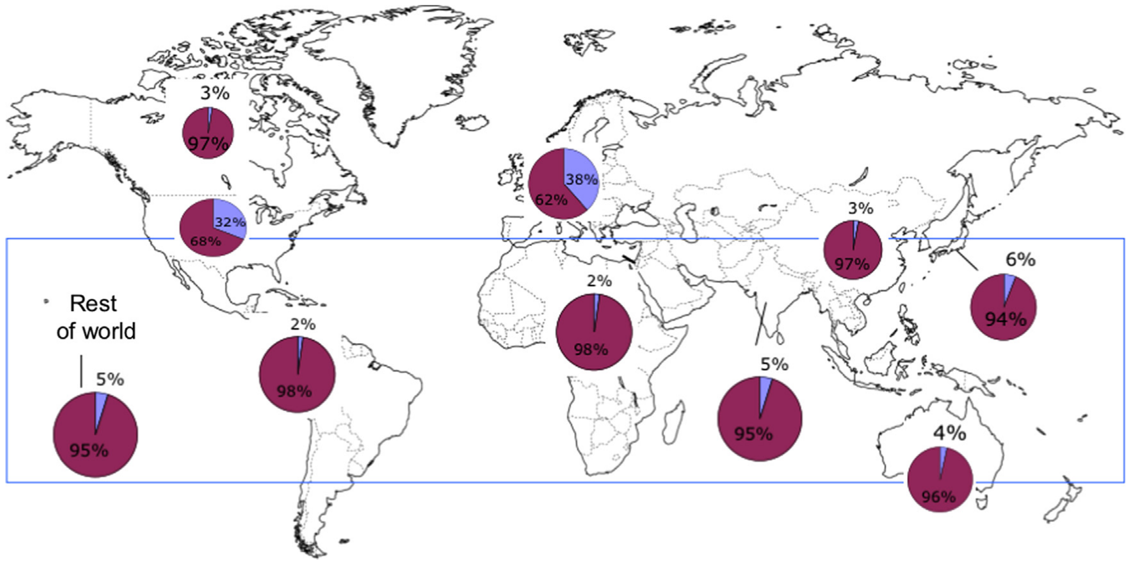

Fig. 2. A map indicating the regional distribution of academic publication activity relating to algae biofuel. Publication data is based on a keyword search of the SCIE database for "fuel AND alga*" between 1974 and 2010. The blue box indicates the 'golden zone' within which algal growth is most favourable.

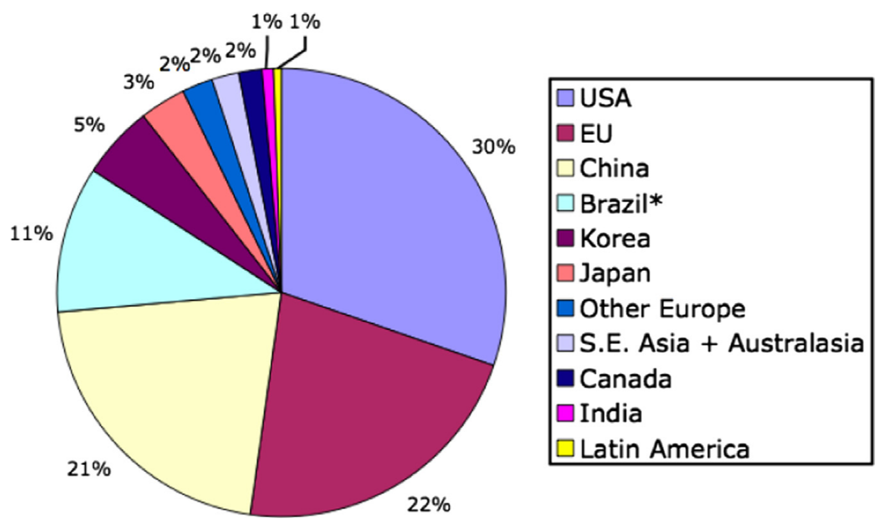

Fig. 3. The geographical distribution of biofuel patent applications granted over the period 1980–2009. The cumulative number of patents granted was determined by querying the Espacenet and BPO databases.

Of course, these two metrics of innovation do not capture all of the activity related to the development of a particular technology and there are many initiatives, funding efforts and research centres in developing countries which are not described here but which are making important progress in algae biofuel. Brazil for example has a pilot plant operated by the Federal University of Rio de Janeiro and South Africa's Council for Scientific and Industrial Research is engaged in internationally recognised algae biofuel research (CSIR, 2009; UFRJ, 2013). These metrics also do not provide any indication of the quality of individual publications and patents. This neglects that individual researchers and firms in countries which have an overall small research output, may be performing innovative work. However, we argue that for any country to benefit from a competitive internal market in a new technology, or to develop a product that can compete internationally then there should be some evidence of domestic research. Taking Brazil's comparative success in the development of first-generation biofuels then we see that in a similar search of the ISI database (not shown), it is ranked seventh in total publications in this area. This combines with its fourth position in biofuel patents to give a reasonable explanation of its success in this area. Its previous success and technological familiarity may also be useful in capitalising on any eventual algae biofuel industry, however, for countries which have no existing R&D infrastructure or historical experience with a related biofuel industry then the challenge is much greater.

Whilst it could be argued that even though most of the innovation activity in relation to algae biofuels is taking place in developed countries, that does not mean that the benefits will not spill-over into other countries. Technology transfer initiatives could also promote wider diffusion under the right conditions. The development of transgenic, insect resistant Bt cotton for example, was led by companies such as Monsanto in the USA but is now widely grown across South America, particularly Argentina (Traxler, 2006). However, whilst the USA benefited from both the increased productivity of its farmers and the increased profits of its biotechnology sector, the receiving countries only benefited from the extra farm productivity. In order to capture the full value-chain, develop export products, and ensure that there is sufficient knowledge base within the country to evaluate and exploit new opportunities then it cannot be enough for developing countries to simply wait for technology spill-overs and transfers. The results shown in Figs. 2 and 3 indicate that many developing nations are not sufficiently involved in the development of a technology that may be of significant advantage to them.

3.4. How much fuel could algae supply?

Producing biofuels from algae could allow developing countries to reduce their consumption and imports of fossil fuels. This is an attractive aspect of algae technology as it would mean more finances could be directed towards development projects. However, estimating the extent to which algae biofuel could reduce oil imports is difficult giving the many different variables surrounding algae species, growth rate, insolation, open pond vs. PBR, and land availability. Ultimately, such estimates will have to be taken at individual project, national, and global scales, and caution must be exercised to avoid over-optimistic projections. However, Lee (2011) offers one set of scenarios based on a general equilibrium model which attempts to forecast the effect of strong government support in both developed and developing country situations. This 'strong support' assumes that algae biofuel costs decrease by 25% each year. Using this model, which is based on economic parameters rather than technical and bio-physical constraints, algae biofuel could supply 7.1% of developed world fuel demand by 2040 whilst in developing countries the figure is only 0.5%. Without support, the figure for developing countries was around 0.1%. Similar results have also been reported at a global scale by Takeshita (2011). The difference in outcomes is due to the greater flexibility enjoyed by developed countries in adjusting industrial and economic policy to cope with external changes (Greenspan, 2005). It also highlights the fact that realising the potential of algae biofuels will depend on not just techno-economic factors, but also socio-political factors too.

Although an algae biofuel industry should have a lower land-use impact than the existing crop biofuel industry, the impact could still be significant. Using a lifecycle analysis approach, Shirvani et al. (2011) estimated that for algae with a biodiesel yield of 850 GJ/ha/yr, a land-mass of 57.3 million hectares would be required to replace the current total annual production of 1.1 billion tons of petroleum-derived diesel. This approximates to an area slightly larger than Spain. No figures are given on the possible indirect land-use change that would result. Using a different methodology employing bio-physical, water, energy, and geographical data to drive a simplified open pond algae growth model, Wigmosta et al. (2011) estimated that algae biofuel could supply 19% of U.S. petroleum needs. They estimated that this could be done using 43 thousand hectares of non-arable U.S. land (about 5.5% of the contiguous US landmass). However, although these areas quoted are substantial, they are not impractical. The kind of careful site evaluation conducted by Wigmosta et al. (2011) needs to be extended to other regions, particularly developing regions, in order to give realistic estimates of the land available for algae cultivation.

4. Are algae-based biofuels commercially viable in developing countries?

The commercial production of algae biofuel is yet to take place, leaving a large degree of uncertainty in existing estimates. This uncertainty is compounded in developing countries as most studies have focused on U.S. or European conditions. However, a growing body of literature has reported that algae biofuel production is technically and economically viable within the next ten to twenty years (Chisti, 2007, 2008; Hanotu et al., 2012; Norskera et al., 2011). Given the high variability in price of conventional diesel in the past 16 years, which has ranged between $1/gallon and $4.70/gallon (EIA, 2010), then developing alternative fuel sources, such as algae, could also provide countries with greater energy stability. However, given that the biofuel cost is currently closely related to the price of fossil fuel, as there are so many fossil energy inputs into biofuel production, then this stability will only occur once biofuels displace a significant amount of fossil fuels. The lack of accurate estimates and commercial sensitivity of the data makes comparative cost per gallon difficult to determine.

Kovacevic and Wesseler (2010) attempted to estimate the direct cost of algae biofuel production based on economic modelling. Assuming linear technical progress and that crude optimistically remained at $100/barrel, then by 2020, algae biofuel could cost €51.6/GJ. This includes taking into account of the energy recovered from methane produced using the algal cake by-product. In comparison with rapeseed biodiesel at €30.5/GJ (taking into account the energy recovered from using the rapeseed cake and glycerol by-products) and fossil fuel at €18.4/GJ (Kovacevic and Wesseler, 2010), algae biofuel will continue to remain uncompetitive with other biofuels unless either greater technical progress or other policy support is provided. Kyoto treaty initiatives such as emissions trading schemes and the clean development mechanism (CDM), which were set up to provide market incentives to invest in clean energy technologies, could significantly improve the feasibility of algae biofuel projects in developing countries. Darzins et al. (2010) and Gao et al. (2011) estimated that with a CO_2 price of between $100 and 200/ton, and provided algae have an oil content of 60%, then a algae-derived biodiesel could become significantly more profitable. However, with regards to the CDM, despite the fact that biofuel projects qualify, as of 2009, none have actually been supported (Wolde-Georgis and Glantz, 2009). An ambitious claim from the US military, reported by *The Guardian* newspaper, suggested that they could produce algae biofuel for jets for under $3/gallon (≈$23/GJ, presumably excluding any by-products) if large scale production by the Defense Advanced Research Projects Agency (DARPA) commences in 2013 (Goldenberg, 2010). Unfortunately, DARPA gave little detail on how they intended to achieve this.

4.1. The algae nutrient industry as a stepping-stone to biofuel production

Scientific research efforts have focused on microalgae that are already commercially significant with the greatest prospects for highly efficient energy production coming from species such as *Chlorella, Spirulina, Dunaliella* and *Haematococcus* (Bruton et al., 2009). These algae varieties are already established in commercial non-fuel operations, where there are used to make a variety of high-value products for use in human and animal nutrition, aquaculture, and cosmetics (Spolaore et al., 2006). The geographic location of these commercial operations is indicated in Fig. 4. The map is based on information contained in Spolaore et al. (2006).

Whilst not all existing producing countries may be contained in the figure, it does indicate where the most substantial industries exist. The figure shows that nearly all the algal production is being carried-out in the climatically suitable zone, with the USA having the most diverse range of facilities. Production facilities exist in non-OECD countries such as India, China, and Burma, but other developing countries have no identified commercial algae industry. Further research is needed to provide complementary data on the distribution of demonstration algae biofuel projects. However, by comparing Fig. 4 with Figs. 2 and 3, which showed the geographic distribution of academic and patent activity in relation to algae biofuel, it could be suggested that the USA, India, China,

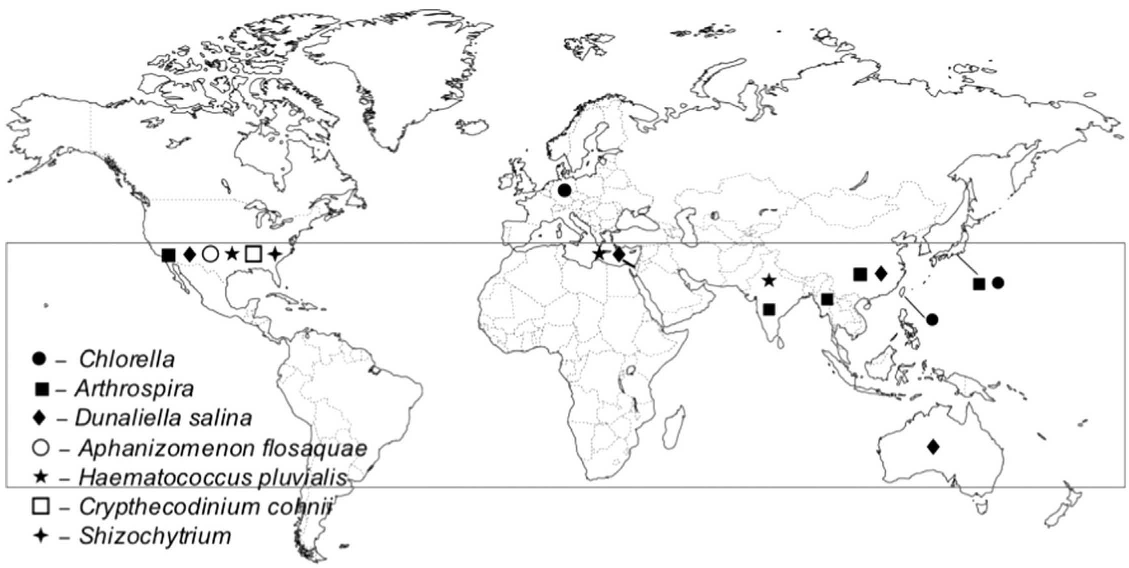

Fig. 4. The geographic location of existing microalgae industries for the production of high-value food and animal feed additives, aquacultural products, and cosmetics. The map is drawn based on data contained in Spolaore et al. (2006). The area inside the box represents the climatically favourable regions of the world for microalgae growth.

and Japan are attempting to develop their comparative advantage in terms of existing expertise and climatic suitability for algae into the new area of biofuel. Europe on the other hand, which has no existing nutrient algae industry, as shown in Fig. 4, may be attempting to leverage its well-developed innovation system to gain a foothold in this newly emerging field. This explains its large share of academic and patent activity as shown in Figs. 2 and 3.

The existing algae growth industry is a small-volume/high-value industry and exists in only a small number of locations, as shown in Fig. 4. Whilst the current cost of fuel production from algae is uncompetitive, this overlooks the possibility to value-add by co-producing fuel and high-value non-fuel products. Stephens et al. (2010a) have argued that incorporating the returns from the sale of non-fuel products from algae farms (by-products including salt, beta-carotene extracts, food supplements and proteins) greatly increases the economic viability of such projects. The study did not look at the effect of reducing costs further by the use of wastewater treatment or carbon credits. They also demonstrate that, with time, decreases in construction costs, and increases in productivity, allow a transition from the small, high-return non-fuel market to the low-return but much larger, energy markets. This greatly increases the range of market entry options and promotes greater competition which could be of benefit to enterprises in developing countries.

4.2. Existing projects and investments

Currently, only a few advanced developing countries like China and India are funding algae-based biofuel R&D collaborative projects between universities, research institutes and industries. In developed countries, an increasing number of private companies and public investment have been committed to accelerate a surprising diversity of algae-based biofuels novel technologies, business models and product strategies. For example, a collaborative R&D venture between Exxon Mobil and Synthetic Genomics worth $600 million was committed to algae based biofuels (Thurmond, 2011). In addition, in 2008, a consortium of commercial, government, and philanthropic investors including the Gates Foundation, the Rockfeller Foundation, the US Department of Energy, BP, Chevron and the UK's Carbon Trust invested over $300 million towards commercialization of algae biofuels (Thurmond, 2011).

The vast majority of algae-based biofuel development is currently being led by industrialised countries but the potential impact of algae technology could be greatest for developing countries, in relation to the potential for employment and greater economic utility from the land. To ensure that the development of an algae biofuel industry does not become a new form of the 'Resource Curse', where the natural resources and cheaper labour available in developing countries supply the raw material whilst the high-value end products and profits are produced elsewhere (Humphreys et al., 2007), then governments and citizen groups in developing nations must consider how they can use financial, legal, and institutional instruments now, to provide for a more equitable distribution of the benefits later. The experience of China, which has successfully developed its own scientific and industrial base partly through investing in an indigenous innovation system and partly through explicit technology partnerships with advanced nations and companies may provide a model for how this could work (Gallagher, 2006).

5. Relevance of advanced technology for algae biofuel production: Potential role of modern biotechnology

The growth of algae is limited by lack of technology to efficiently and economically produce biofuel. Advanced technology will form part of the multidisciplinary approach needed to achieve the full potential of algae for biofuel production (Wijffels and Barbosa, 2010). Agricultural revolution through the introduction of breeding programs and large scale selection played a significant role in achieving biomass productivity in advanced developing countries such as India and China, particularly during the green revolution of 20th century (Conway, 1998). Large scale production of microalgae has great potential to achieve similar goal through the adoption of advanced modern technology. The application of modern biotechnology is likely to play an important role in the whole chain of process development including strain development, scale-up, bioprocess engineering, bio-refineries and integrated production. Modern biotechnology, particularly genetic engineering but also conventional methods of strain selection have great potential to improve the production efficiency, and reduce the costs that are associated with algae-based biofuel (Beer et al., 2009; Radakovits et al., 2010). The main focus of these efforts is to produce algae which have a greater efficiency of converting light to biomass, a greater lipid (oil) content, a greater ease of processing/refining, and greater adaptability to different growing conditions (Beer et al., 2009).

Genetic modification (GM) of algae can provide the important breakthroughs needed through the gene manipulation while unravelling the barrier to understand the metabolic pathway of algal genome (Beer et al., 2009). Several studies (Adenle, 2011; Brookes and Barfoot, 2010; James, 2012) have shown the importance of GM technology particularly with regards to environmental and socio-economic benefits. For example, creating desired GM traits such as, faster growth and higher yields, drought tolerant crops, disease and pest resistant crops, by using less dangerous chemicals. All these GM traits can be selected within a short given period of time. This approach would be beneficial to speed up selection process for microalgae species (Radakovis et al., 2010). For example, genetic engineering/GM technology is required to understand the complex metabolic activity and energy storage of algae so as to regulate uptake of nutrients and the production of lipids and carbohydrates (Scott et al., 2010). Added to this, genetic engineering can specifically target genes to create new algal strains with higher efficiency. Genetic engineering or transgenic approach still require a great deal of work for large scale production of new algal strains (Larkum et al., 2012). But the critical question remains as to how easy it will be for developing countries to take advantage of advanced technologies such as genome manipulation, DNA sequencing, and bioinformatics, in the light of weak biosafety regulatory system and inadequate capacity building. And the unknown threats of genetically modified organisms (GMOs) to the environment and long-term impact on human health represents a primary concern in developing countries. For example, in African countries, the issue of possible contamination of conventional crops called "traditional heritage" by GMOs was emphasized among the key stakeholders such as scientists and policymakers (Adenle, 2012).

Marker assisted selection is another biotechnological tool that can be used to select or isolate highly efficient non- GMO strains for algae production. Several studies (Day and Goldschmidt-Clermont, 2011; Lumbreras et al., 1998; Pereira et al., 2011; Sizova et al., 2001; Zaslavskaia et al., 2000) have shown efficient isolation of microalgal transformants by the use of selectable markers. Pereira et al. (2011) describe a high throughput screening techniques for lipid-rich strains to isolate fast growing microalgae-it is regarded as a user-friendly, fast procedure than most common method for microalgae selection.

For developing countries though which may have little access to some of the facilities and expertise required to undertake such research programs then another strategy may be proposed. Whilst the US Aquatic Species Program was one of the largest attempts to screen, breed, and evaluate algae species for fuel production, studying over 3000 species there remain many thousands of species to be studied (Sheehan, 1998). The more modest technology required to undertake such a program may be more feasible for the limited resources available to many developing countries which can be achieved through bioprospecting. There are over 40,000 species of microalgae with further opportunities for bioprospecting to identify strains that possess the desired characteristics (Hu et al., 2008). This approach has been employed in searching for unstudied algae strains that may exist in unexplored habitats within their borders (Mutanda et al., 2010). In Iran, research is underway into a new algae species that has been discovered to thrive in the salty waters of Lake Orumieh (Najafi et al., 2010). Similarly, a program in South Africa has successfully screened over 200 organisms to determine their lipid content (Maharajh and Harilal, 2010). Such approaches make great use of the abundant biodiversity that exists in these countries where modern biotechnology has significant role play a significant role.

While bioprospecting can be important in identifying desirable biofuel algal traits (Radakovis et al., 2010), a combination of transgenic approach and conventional breeding including marker assisted selection is fundamental to achieving large scale production of desired algal strains (Day and Goldschmidt-Clermont, 2011; Larkum et al., 2012; Radakovis et al., 2010). As for transgenic approach, it must undergo regulatory and public scrutiny in terms of its potential impact on human health and environment. Again, the biosecurity implications of using GMOs, as well as intellectual property (IP) enforcement and ethics have led to some concern about these approaches (Lee et al., 2008; Qiam, 2009).

Parayil (2003) cautions that the innovation systems and guiding principles behind the Green Revolution, which relied on a network of co-operation between western aid agencies and developing nation governments, research institutes in developing countries, and local and foreign universities, worked towards a goal of eradicating hunger. In contrast, the drive behind the use of genetic engineering for both food and fuel uses is one motivated by private gain, with little involvement of developing nations and citizens themselves (Parayil, 2003). This does not exclude the possibility that biofuel from GMOs may contribute to sustainable development in low-income countries but the motivations behind its use must be clearly articulated in order to avoid conflicts between the different stakeholders involved and recognising the difference in power relations that exist between well-funded global companies, cash-strapped local governments, and potentially vulnerable individual citizens.

6. Challenges and policy implication

While the commercial cultivation of algae is already technologically feasible for the small-scale production of animal feed and nutraceutical products, the production of algae biofuel on a commercial basis is far from being realized. There are numerous technical challenges and uncertainties associated with large-scale algae biofuel production. The extent of this uncertainty must be acknowledged, especially before any recommendations for investment or policy change which would affect the extremely limited finances available in developing countries, can be made. Based on the literature reviewed in this paper and using the data presented in Figs. 2–4, it is possible to identify a number of trends in relation to algae biofuel in general, and the implications for developing countries specifically. From this we will outline a range of technical, environmental, and institutional/political challenges that must be overcome before algae biofuel can contribute to the sustainable development of developing countries. General recommendations for decision-makers in developing countries who are considering how best to develop a nascent algae biofuel industry are then proposed.

6.1. Water and energy

The difficulties of finding fast-growing algae strains with high photosynthetic efficiency and oil content, easy harvesting systems for algae culture, as well as cost-effective photobioreactor designs will remain big obstacles to successful commercialization of algae biofuel production. Supporting infrastructure costs, as well as the costs of operation and maintenance are estimated in a number of feasibility studies (Gao et al., 2011; Norsker et al., 2011; Scott et al., 2010; Singh and Gu, 2010; Stephens et al., 2010a).

Moreover, some algae cultivation processes have scale-up challenges as they require many compartments, support materials and water demands. Large quantities of water demand for vast ponds, in addition to evaporation losses and climatic variability, create some concern especially where either water reclamation or wastewater treatment is not an integral component of the cultivation process (Ryan, 2009). Algae cultivation could also add to the pressure on water supply already created by other agricultural crops—a problem in the many water-stressed areas where algae production is being suggested. In open pond systems, high evaporation rates may impact water demand and humidity levels and this will necessitate some amount of water to be discharged continuously (alternatively remediated and reclaimed) to prevent salt accumulation in the algae cultivation process which may impact ecosystems. A recent study using life cycle analysis argues that open pond algae cultivation for biofuel production tends to have more environmental impact in water use than conventional crops, based on US geographic data (Clarens et al., 2010).

Energy inputs are required for water processing of algae cultivation. For example, energy is needed to filter algae from water, in the disposal of sludge and pumping water between ponds. According to Murphy and Allen (2011), the greatest energy requirement comes from pumping water between ponds. The energy requirement for algae production and maintenance for recovery could impose obstacles to sustainable scalability, specifically with regards to management of process water exposed to chemical additives (Ryan, 2009). Murphy and Allen (2011) found that seven times more energy needs to be invested in water management for cultivating saline, eukaryotic algae in open ponds, compared with the expected energy return from the extracted biodiesel. The same study notes that the amount of energy required depends on the rate of growth of algae species, types of production systems and environmental conditions. Again, this reflects the great uncertainty surrounding the technology.

6.2. Soil and land-use

Photobioreactors and open raceway pond systems may require vast areas of undeveloped and relatively level land to be converted to algae production (Luo, 2010). Wigmosta et al. (2011) suggests a slope of 1% as a suitable maximum. Construction of these systems, along with supporting road and other infrastructure, may impact existing soils (either by degradation or compaction) and cause removal of vegetation (Assmann et al., 2011). Soil compaction is a problem as it reduces the pore space in the soil, reducing permeability, and along with vegetation removal leads to greater surface runoff and erosion, reducing local water availability. This can cause potentially serious and long-lasting ecosystem damage and reduced local water availability (Castillo et al., 1997).

Moreover, biological organisms in the soil may be disturbed through the large scale commercial cultivation of algae (especially open pond). However, the severity of the effects will depend on the degree to which groundwater infiltration is impacted by impervious surface and the health of watershed, which is partly determined by soil type and permeability. Given the technical simplicity of open pond systems, a scalable open pond system may perhaps transform millions of hectares of land towards the cultivation of biofuel feedstock (Ryan, 2009). Careful feasibility and impact assessments should be conducted prior to construction to ensure minimal ecological impacts, although the level of competition for productive or ecologically sensitive land is expected to be relatively low for algae production.

For first generation biofuels, Wicke et al. (2011) estimated the percentage of land in arid and semi-arid areas available in sub-Saharan countries ranged between 1.5% and 21%, excluding ecologically sensitive zones and steep terrains. Arezki et al. (2012) also estimated around 200 million hectares of available uncultivated land in the world (defined as land which has high potential for rainfed agriculture, low population density, and not forested or protected) is located in sub-Saharan Africa. Africa as a whole is 3 billion hectares. Algae biofuel can be produced on the least productive sub-set of the available land, and produce the same output as first generation biofuels over a much smaller area (see Section 2.2). Considering the higher technical needs of algal biofuel production, suitable areas are likely to be defined by access to e.g. stable electricity supply, pipelines, and road infrastructure rather than the productivity of the soil. While it is possible that such facilities may compete for land with other agricultural crops, leading to indirect forest conversion elsewhere for producing the displaced agricultural commodities, the level of competition for arable land arising from algal biofuel production will be minimal since algal biofuel facilities can be built on unproductive land.

6.3. Biosecurity and intellectual property

Apart from the long-term physical impact of commercial-scale open pond cultivation on ecosystem health, the use of GM algae for algae biofuel production can be another threat to the sustainability of the local ecosystem. Conserving biodiversity is especially crucial in developing countries and introduction of invasive alien species can threaten biodiversity (Ditomaso et al., 2010). If GM algae are used for biofuel production then this will be a critical environmental issue. Concern already exists about the potential for GM food crops to escape into the natural environment and cause loss of biodiversity due to the displacement of naturally occurring organisms (Wolfenbarger et al., 2000). A precautionary approach is recommended due to risks of GMO cross-breeding with wild species, as has occurred with canola, or the emergence of herbicide-resistant weeds (Owen and Zelaya, 2005). Competent authorities and transparent independent assessments should be encouraged to assess GM algae risks and opportunities (Lunquist et al., 2010), particularly with regards to biosafety and regulatory issues. Guidelines as stipulated in key international agreements, such as governed the Cartagena Protocol on Biosafety of Convention on Biological Diversity (CBD), provide a safe guard on the propagation of GMOs. Other international regulations developed under the auspices of the United Nations World health Organisation (WHO) and Food and Agricultural Organisation (FAO) should also guide the release of GMOs in developing countries (CBD, 2000; FAO/WHO, 2000). Such issues can be especially difficult to resolve in developing countries where effective enforcement, rather than legislation, can be a major limitation.

The use of GM algae also raises other issues concerning intellectual property protection. If the developing country is relying on the cultivation of proprietary organisms from overseas for biofuel production (or for bioprospecting and R&D of native strains), they must be able to demonstrate that they have the appropriate IP protection regime in place if they wish to collaborate with foreign companies. Developing countries may lack the resources to enforce IP or to afford the high premiums of imported technology with associated IP. For example, the cost for completing regulatory compliance for introducing GM virus-resistant rice in Costa Rica was $2.25 million (Cohen, 2005). The absence of such IP protection may hinder GM algae deployment in developing countries. International negotiation for harmonizing and stimulating trade through organisations such as the World Trade Organization may be useful in this regard. However, the social acceptability of such moves to the broader population must also be taken into account to avoid the ‘exclusion effect’, described by Parayil (2003) as the tendency on the part of peasant farmers to resist modernization and technological innovation.

6.4. Institutional capacity

Fig. 5 shows a diagram representing the status of algae biofuel development. Regions and countries are allocated into four groups

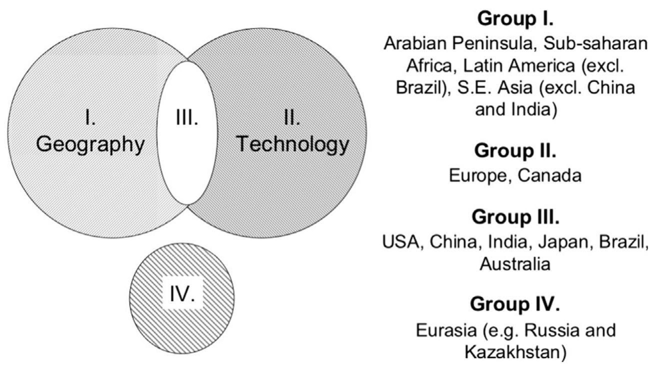

Fig. 5. An assessment of the status of algae biofuel in the major regions and countries of the world. Group membership was assigned based on position within the climatic 'golden zone' and existence of scientific R&D programs.

according to their possession of two significant attributes—location within the 'golden zone' for algae growth, and existence of scientific expertise (as assessed by academic publication activity). Group III countries such as the USA and China, are thought to be best placed to benefit from the development of an algae biofuel industry. However, many of the poorest countries for which the supposed benefits of such an industry are supposed to be greatest, lie within Group I. The lack of indigenous skills and expertise may present a major barrier to encouraging business development and private investment, whilst also making the task of appropriate regulation and support by relevant local agencies and governments, more difficult.

The previous history of attempts to promote biofuels in developing countries raises questions about how successful cooperation can be promoted in any new algae industry. Of 300 biogas plants installed in Kenya between 1980 and 1990, only 25% are thought to still be working (Amigun et al., 2008b). Similarly, over-optimistic projections for the potential returns from planting Jatropha have been followed by disappointing returns on investment in countries such as India, China, and Tanzania (Kant and Wu, 2011). A well-established physical infrastructure (electricity, roads etc.) and social infrastructure (higher education, courts, and banks) is lacking in many of developing countries which will add to the cost of production and increase project risks.

7. Policy implications

Due to the great uncertainty surrounding this technology and the importance of many local factors related to natural resource and human capital endowments, it is not possible to make specific recommendations. However, we have highlighted the issues and difficulties that individual nations and business interests should consider if they wish to prepare for or promote an algae biofuel industry. Here we list some steps that policymakers may wish to consider to ensure that algae biofuel forms part of a sustainable development plan.

7.1. National energy policy

A growing number of developing countries are announcing biofuel activities but these projects are often piecemeal and do not form part of an overall long-term strategy for meeting future demand, increasing access (particularly for the poor, and in rural areas), and reducing dependency on fossil fuel imports. Amigun et al. (2008a) criticises many national energy plans in African countries for being unavailable, out of date, or inadequate. The setting of clear national targets for algae biofuels to create a positive business environment and providing government support (e.g. subsidies, supportive financing etc.) is necessary to stimulate investment in this immature technology. Drawing on the previous experience of 1st and 2nd generation biofuels can help in selecting effective measures and avoiding previous pitfalls.

7.2. Regulation of fuels and organisms

Any new fuel must be subject to appropriate testing and regulation to ensure that it can be safely used in either transport or home applications. The introduction of previous biofuel blends such as E10 (10% biofuel 90% fossil fuel) which contained gasoline and 10% ethanol was achieved with relative ease as most car engines were able to deal with the different performance characteristics without the need for modification. Higher blends such as E85 (85% biofuel 10% fossil fuel) require engine modification and newer technology which may not be appropriate for developing countries where the infrastructure and many vehicles are substantially older than found in developed countries. Most modern diesel engines do not require engine modification provided high quality biodiesel is used (Gerpen, 2005). To an extent much of this verification and standards-setting will already be carried out during product development by international companies and relevant organisations. However, relevant national government agencies should ensure that they are aware of these developments and take the necessary steps to incorporate them into their own legislation and policies. Aviation fuel is one such area which is highly regulated and the certification of new algae-based jet-fuel for commercial use, e.g. Continental airlines tested a 50/50 algae-jatropha biofuel blended jet-fuel in 2008 (Marsh, 2008), will take a number of years.

Careful attention must also be paid to the regulation of new algae organisms, particularly if those algae are being imported from outside the country or have been genetically modified. In the same way that any new pharmaceutical or GM seed crop needs to be regulated in each new region it enters, both to ensure compliance and suitability for use in the local context, then regulatory frameworks need to be established for the emerging algae industry. As well as addressing the biosecurity issues, developing countries should also consider how to protect their own intellectual property contained in indigenous algae species and reassure foreign investors that imported IP and technology can be protected.

7.3. Education and R&D

Given the limited resources available for R&D and industrial support in developing countries, then careful consideration needs to be given as to whether support for algae biofuel should form part of their policies to promote greater access to clean energy and raise living standards. The data presented here indicates that there are few researchers and professionals with knowledge and experience of the emerging field of algae biotechnology within many developing countries. This may make assessing potential projects and designing appropriate policies difficult to achieve. It also means that the potential resources (both geographical and biological) that are native to many developing countries are not being properly researched and evaluated to determine if they can contribute to national development. Whilst it may not be possible to undertake the kinds of high-technology screening and process development R&D being undertaken in the US, EU, China and India, it may be possible to divert some attention to feasibility studies and native algae study. Such work in native bioprospecting could be valuable when trying to form collaborations with international academic and investment partners, and achieve gains in algal lipid productivity without importing foreign patented strains.

There is also a need to improve public awareness and education about advances in biotechnology in order to ensure that exclusion effects are avoided and that the citizens from the poorest backgrounds and rural areas are able to actively participate in shaping how their land and the land around them is developed. It is important too, that those providing that information are properly informed about the potential benefits and drawbacks of promoting a new industry such as algae biofuel (particularly if it involves GM algae), particularly to avoid over-selling which can create problems and distrust in the long-term. Again the experience of the Green Revolution which encompassed not just the development of new crop strains but also technology transfer in terms of setting up new agricultural universities, training programs, irrigation schemes, and financing options provides a model of how this may be achieved.

8. Conclusion

For developing countries, particularly those with the lowest incomes, it is a difficult balancing act in deciding how best to support an immature, but potentially highly lucrative, industry with the more immediate needs of citizens for basic healthcare and education. With respect to algae biofuel, there too many uncertainties (e.g. environmental impacts, technology choice, algae productivity etc.) and unknowns (e.g. future fossil fuel prices) exist to recommend that public money or development aid should be used to support such an industry at this stage. In these situations it is perhaps best to offer administrative and legal support in order to provide either local businesses or appropriate foreign organisations with the framework in which to safely undertake preliminary studies and demonstration plants for algae biofuel.

A different conclusion can be drawn for emerging markets such as China, India, and Brazil, which are better placed to undertake greater risks with investment in new technologies. There is of course a difficulty in continuing to refer to the world's second largest economy as a 'developing country' and similarly with respect to India and Brazil which are home to world-leading companies and research institutes. Nonetheless, despite the rapid economic growth enjoyed by these emerging world powers in the last two decades, this growth has been very unevenly distributed. These emerging powers are well-positioned to build on their existing crop biofuel and nutrient algae industries to develop an algae biofuel industry. The significant R&D activity taking place in China and India indicates that these countries are keen to develop such technologies independently and gain a first-mover advantage. However, there is a concern that focusing attention on such technology will do little to address the needs of those who have so far failed to benefit from the rapid economic growth. A critical eye must be kept on algae biofuel technology to ensure that its development in both low-income and newly developed economies is such that certain groups and interests are not privileged at the expense of the most vulnerable.

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