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*Review*

# Algae for Africa: Microalgae as a source of food, feed and fuel in Kenya

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**Microalgae are unicellular photosynthetic organisms that inhabit diverse ecological habitats ranging from freshwater and brackish water to seawater and wastewater. They are also especially equipped to thrive in extreme temperatures and pH conditions. Decades of research have highlighted their potential as sources of biofuels, foods, feeds and high-value bio-actives. However, industrial-scale cultivation of microalgae is still not being carried out to its full potential. This review aims to shed light on the potential of microalgal-derived food, feed and fuel in developing countries and to what extent microalgae could be applied to sustainable development efforts with a special focus on Kenya. The Kenyan government has set out a development policy termed 'Kenya Vision 2030' that aims to transform the nation into a newly industrialised country with a high quality of life for all its people by the year 2030. Here we show that, not only does Kenya lie in an optimal geographical region for microalgal cultivation, but that microalgae has the capability to fulfil some of the 'Kenya Vision 2030' goals.**

**Key words:** Algae, biofuels, fertilizer, nutraceuticals, feed.

## INTRODUCTION

Microalgae are sunlight-driven cell factories that convert carbon dioxide ($CO_2$) into potential biofuels, foods, feeds and high-value bio-actives (Chisti, 2007). These peculiarities make microalgae the most abundant organisms on Earth. In the early 1950s, the increase in the world's population and the possibility of an insufficient protein supply imminent, research for an alternative and unconventional protein source was carried out. Microalgal biomass quickly appeared to be a promising candidate (Spolaore et al., 2006). Meanwhile, extensive research into algae for biologically active substances, particularly antibiotics, began (Borowitzka, 1995). Further research focused on environmental technologies aimed at improving the quality of wastewater, and with the onset of the energy crisis of the 1970s, microalgae were then suggested as a source of biomass for methane (Chaumont, 1993).

The microalgal biotechnology field has developed to

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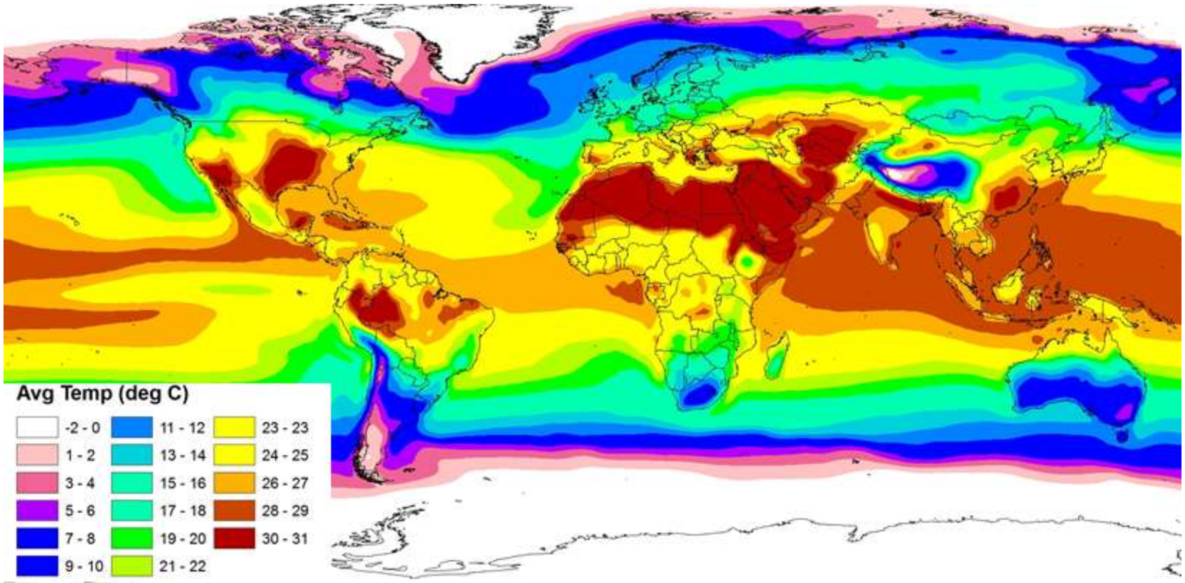


**Figure 1.** Global map of average temperatures (July 2000) (courtesy of Oak Ridge National Laboratory, U.S. Dept. of Energy).

include an array of applications; potential biomass for biofuels, pharmaceuticals, nutraceuticals, nano-technology, bioremediation industries and in aquaculture as feed in for example bivalve, echinoderm, crustacean and fish hatcheries.

But to what extent is microalgal biotechnology applicable to developing countries? This review attempts to identify issues faced by developing countries and how microalgae could be utilised in sustainable development approaches to address these issues. Kenya is still considered a developing country according to the UN Human Development Report (UNDP, 2015), and was chosen as the focus of this review.

## THE CULTIVATION OF MICROALGAE

There are five main parameters required for the successful cultivation of microalgal biomass, light, $CO_2$, water and inorganic salts, and an ideal temperature of between 20 and 30°C.

### Light

Photosynthesis converts light energy, usually sunlight, into chemical energy. When light is the only limiting factor, microalgal productivity becomes proportional to the light conversion efficiency (Richmond et al., 2003; Kumar et al., 2010). At night, or other dark conditions, photosynthesis cannot occur and the microalgae utilise stored energy for respiration. Depending on the temperature and other conditions, up to 25% of the biomass produced during the day may be lost again at night (Chisti, 2007).

The spectral range of light that can be utilised by photosynthetic organisms is between 400 and 700 nm known as photosynthetically active radiation (PAR), making up approximately 45% of the total light spectrum from the Sun (Thimijan and Heins, 1983). Coupled with a maximum efficiency of photosynthesis by microalgae at approximately 27%, the maximum theoretical conversion of light energy to chemical energy by photosynthesis is approximately 11% (Gao et al., 2007).

The climatic zones with optimum growth conditions, based on the average global temperatures and average global solar radiation in Figures 1 and 2, are located between 40° north and 40° south latitude. Kenya lies perfectly on the equator and has an average horizontal irradiance of 2000 kWh/m$^2$ (Figure 3).

### Temperature

Temperature is one of the major factors that regulate cellular, morphological and physiological responses of microalgae: Higher temperatures generally accelerate the metabolic rates of microalgae, whereas low temperatures lead to inhibition of microalgal growth (Kumar et al., 2010). Towards the North and South poles there is a lower light intensity and temperature, which results in lower biomass productivity. Therefore, the equator is considered an ideal location due to the temperature stability (Figure 1). Nonetheless, this does not necessarily mean the highest biomass yields as there are other climatic occurrences that can affect growth (Moody

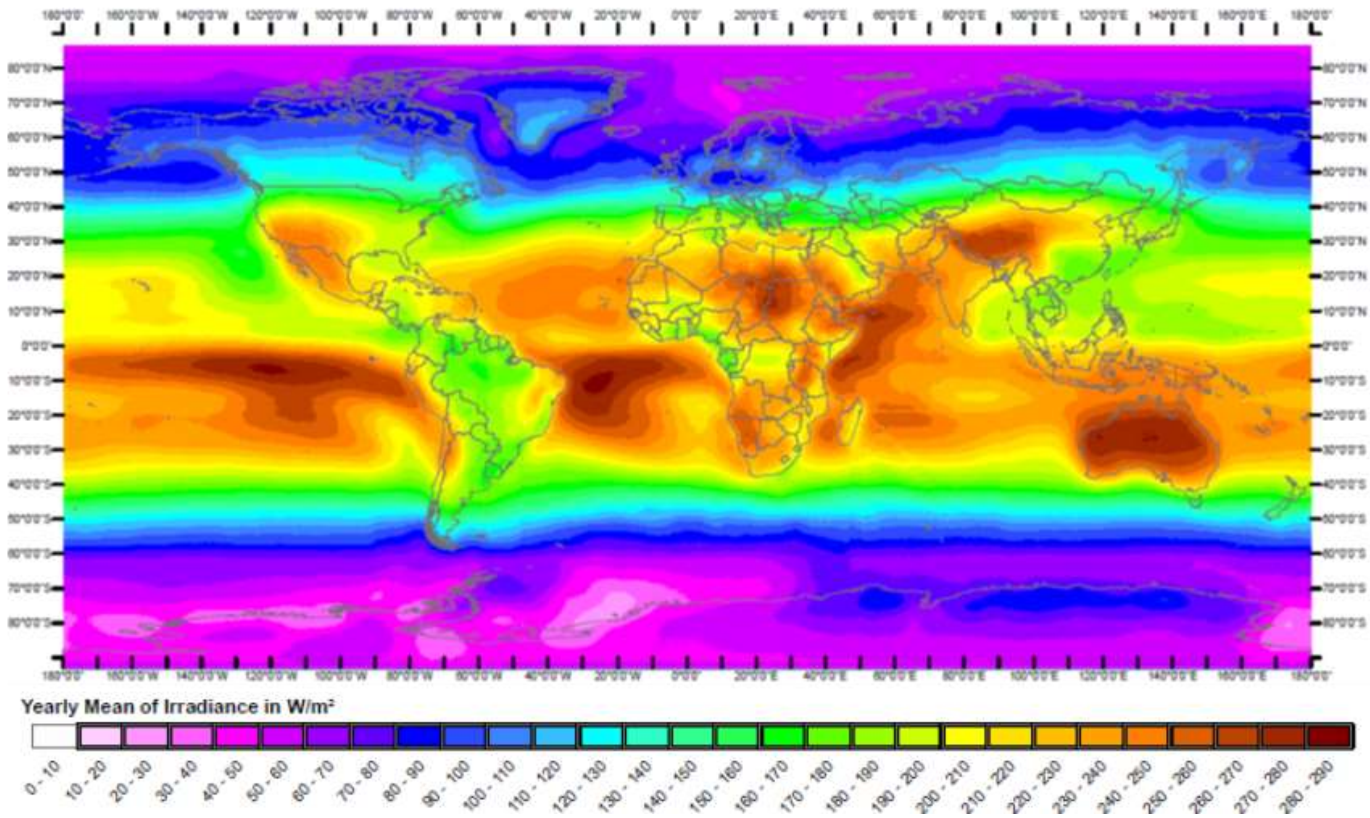


**Figure 2.** Global map of average solar radiation (1990-2004) (reprinted with permission from SoDa Services, Copyright Mines ParisTech / Armines, 2006).

et al., 2014).

Ideal sites are those that do not close due to cold conditions and are able to operate throughout the year as well as producing a high annual lipid yield. High variability results in increased infrastructure which would create further operation costs. A study of the global biofuel potential from microalgae by Moody et al. (2014) showed the western Kenyan city of Kisumu to maintain an average annual temperature close to the optimum and would therefore be able to maintain high biomass yields; making it an ideal location for microalgae cultivation (Moody et al., 2014).

## Carbon dioxide ($CO_2$)

As with all photosynthetic organisms, microalgae predominantly use $CO_2$ as a carbon source. No growth can occur in the absence of $CO_2$ and an insufficient supply of $CO_2$ is often the limiting factor in productivity. Natural dissolution of atmospheric $CO_2$ into the water is not enough; atmospheric $CO_2$ levels are at approximately 0.0387%, which are not sufficient to support the high microalgal growth rates and productivities needed for large-scale biofuel production. Usual sources of $CO_2$ for microalgae are atmospheric $CO_2$, $CO_2$ from industrial exhaust gases (for example flue gas and flaring gas, which typically contain about 4 to 15% of $CO_2$) and $CO_2$ chemically fixed in the form of soluble carbonates (for example $NaHCO_3$ and $Na_2CO_3$) (Kumar et al., 2010). Uptake of these inorganic forms of carbon also has the potential to increase the pH within the cultures (Hansen, 2002). Oxygen ($O_2$) is a product of photosynthesis and levels above atmospheric $O_2$ levels (0.2247 mol $O_2$ $m^{-3}$) can inhibit photosynthesis in a number of microalgal species, even when the $CO_2$ levels remain elevated (Aiba, 1982). Furthermore, elevated levels of $O_2$ coupled with high irradiance can lead to photo-oxidation (Richmond, 1990; Camacho Rubio et al., 1999).

In 2015, Kenya signed the United Nations Framework Convention on Climate Change (UNFCCC) Paris Agreement, a daughter treaty of the 1997 Kyoto Protocol, which aims to empower all countries to act to prevent average global temperatures from rising by more than 2°C (UNFCCC, 2015). Increasing global temperatures can be largely attributed to elevated $CO_2$ (Solomon et al., 2009). Theoretically, microalgae are capable of utilising up to 9% of the incoming solar irradiance, producing 280 tonnes of dry biomass $ha^{-1}$ $year^{-1}$ whilst sequestering roughly 513 tonnes of $CO_2$ (Bilanovic et al., 2009). Implementing microalgal cultivation strategies in Kenya will allow the country to be an active participant in the

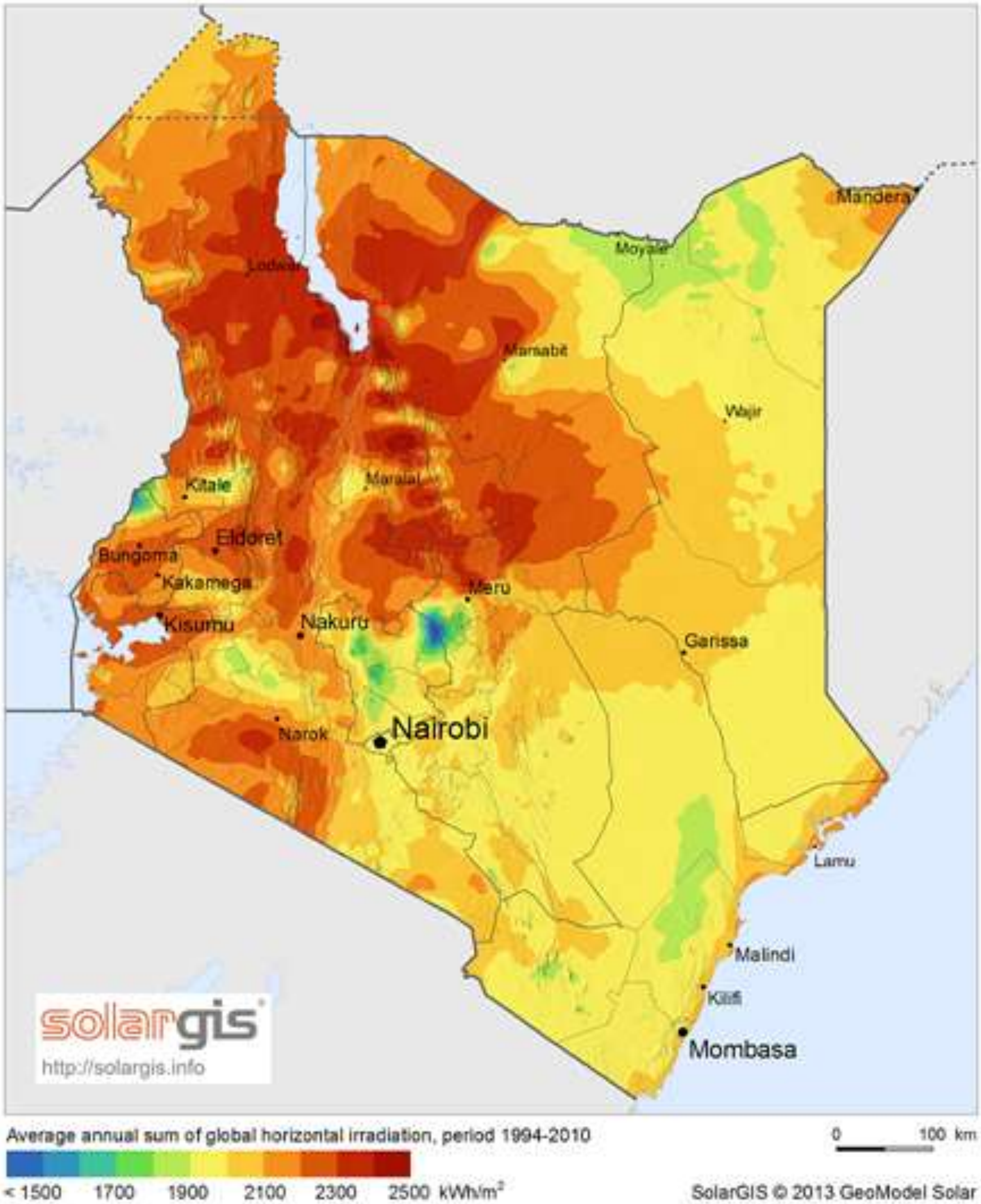


**Figure 3.** Global horizontal irradiation in Kenya (1994-2010) (SolarGIS© 2016 GeoModel Solar).

global efforts to reduce atmospheric $CO_2$ levels.

## Water

Drought is a prevalent natural catastrophe that affects the 10 million mostly livestock-dependent people in the arid and semi-arid lands in the north and north-east of Kenya (Zwaagstra et al., 2010). Therefore, the use of freshwater is not sustainable. However, microalgae are capable of thriving in saline, brackish and wastewater environments.

### *Seawater*

With a coastline stretching 1420 km, Kenya has every possibility to utilise this source of water for algae culture. Kibuyuni, in the south coast of Kenya, has found success in the cultivation of macroalgae (seaweed). Kenya

Coastal Development Project (KCDP) facilitated the construction of seaweed farms and supplied tools, training and seeds. The project has created new employment opportunities, particularly for women, and the income generated has allowed farmers to send their children to school and create better housing for them. The community has managed to produce 10 tonnes of dried seaweed since February 2015 worth 450,000 KSH (£3,064) by exporting to China, Ireland and Malaysia (KCDP, 2015). The implementation of microalgae cultivation farms in the coastal region of Kenya could also be realised. Moreover, utilising seawater would provide trace elements beneficial to microalgal growth. Most bioactive trace metals, including iron, exist at nanomolar (10-9 M) to picomolar (10-12 M) concentrations in our oceans; approximately one-millionth of the intracellular concentration in diatoms (Bruland et al., 1991; Morel and Price, 2003).

### *Wastewater*

Nairobi is one of largest cities in Africa and with a growing urban population; the wastewater generated could be exploited for culturing microalgae. Microalgae grow abundantly in wastewater as it is rich in organic carbon as well as inorganic nitrogen and phosphorus. This can be attributed to the ability of algae to efficiently sequester nitrogen and phosphorus. Oxygen produced by the photosynthetic microalgae would allow treatment of wastewater via oxidation as well as aeration of treatment ponds, without the need of mechanical aeration and thus reducing operational costs. This type of integrated system allows for an economically viable method to both treat wastewater as well as culturing microalgae for biofuel (Mahapatra et al., 2013).

Olguín et al. (2003) describe a system where 84 to 96% of nitrogen and 72 to 87% of phosphorus was removed from the anaerobic effluent of piggery wastewater by growing algae, thereby reducing eutrophication in the environment.

Nevertheless, only 30% of published work on microalgae used wastewater as a source of nutrients, regardless of its promising benefits. The vast majority of laboratory based experiments use chemical fertilisers as it is much more readily available (Lam and Lee, 2012). However, this becomes an issue when up-scaling as the production of chemical fertilisers is energy intensive and not sustainable; 1.2 kg of carbon dioxide is released for every 1 kg ammonia produced (Kim and Dale, 2005).

## Inorganic salts

Apart from the essential need of a carbon source, microalgae require a nitrogen source. Nitrogen is an important constituent of both nucleic acids and proteins; crucial for the primary metabolism of microalgae (Becker, 1994). Phosphorus is another important nutrient required by microalgae for growth. It is indeed the 'staff of life'; the scaffolding on which all biomass is built (Karl, 2000).

Sources of nitrogen and phosphorus include agricultural fertilisers, which are easily available but can be a significant cost factor at a large-scale cultivation level. More cost-effective sources of nitrogen and phosphorus have been explored such the use of wastewater mentioned previously.

## Scaling up techniques

The production of microalgal biomass requires relatively simple photosynthetic growth conditions: light, carbon dioxide, water and inorganic salts (Moejes, 2016b). The system must also include a means of agitation or mixing of the culture to prevent the settling of the microalgal cells, the elimination of thermal stratification (temperature layering effect that occurs in water), distribution of carbon dioxide and inorganic salts, removal of the photosynthetically produced oxygen and the enhancement of light utilisation efficiency (Terry and Raymond, 1985). There are two main land-based cultivation methods implemented for the large-scale cultivation of microalgae; raceway ponds and photobioreactors. A comparison summary can be found in Table 1.

### *Raceway ponds*

Raceway ponds are simple open-air microalgal biomass cultivation systems which have been used for the large-scale cultivation of microalgae since the 1950s. They are typically made of a closed loop recirculation channel that is typically 0.3 m deep. The mixing (and circulation) is achieved by the implementation of a paddlewheel (Figures 4 and 5) which must operate continuously to prevent sedimentation. Broth is harvested behind the paddlewheel. The building materials utilized for raceway ponds are concrete, compact earth, and may be lined with white plastic (Chisti, 2007).

As carbon dioxide is the carbon source for algae, its sequestration from the air into the culture limits the growth rate. Other major bottlenecks of raceway ponds are the lack of temperature control (any cooling is only achieved by evaporation, and any heating will add to the production cost) and the susceptibility to contamination by other organisms including other algal strains that might out-compete the desired species (Borowitzka, 1999; Moejes et al., 2016a).

### *Photobioreactors*

Photobioreactors are closed microalgal biomass cultivation devices that allow for the production of a monoseptic culture which is fully isolated from a potentially contaminating environment (Grima and Fernández, 1999). Although there are a number of

**Table 1.** Comparison of raceway ponds and photobioreactors (derived from Pulz, 2001).

| Culture system | Raceway ponds | Photobioreactors |
|---|---|---|
| Required space | High | For photobioreactor itself, low |
| Water loss | Very high, may also cause salt precipitation | Low |
| $CO_2$ loss | High, depending on pond depth | Low |
| Oxygen concentration | Usually low enough because of continuous spontaneous outgassing | Build-up in closed system requires gas exchange devices ($O_2$ must be removed to prevent inhibition of photosynthesis and photo oxidative damage) |
| Temperature | Highly variable, some control possible by pond depth | Cooling often required (by spraying water on photobioreactor or immersing tubes in cooling baths) |
| Shear | Usually low (gentle mixing) | Usually high ( fast and turbulent flows required for good mixing, pumping through gas exchange devices) |
| Cleaning | No issue | Required (wall-growth and dirt reduce light intensity), but causes abrasion, limiting photobioreactor life-time |
| Contamination risk | High (limiting the number of species that can be grown) | Medium to low |
| Biomass quality | Variable | Reproducible |
| Biomass concentration | Low, between 0.1 and 0.5g/l | High, generally between 0.5 and 8g/l |
| Production flexibility | Only a few species possible, difficult to switch | High, switching possible |
| Process control and reproducibility | Limited (flow speed, mixing, temperature only by pond depth) | Possible within certain tolerances |
| Weather dependence | High (light intensity, temperature, rainfall) | Medium (light intensity, cooling required) |
| Start-up | 6 – 8 weeks | 2 – 4 weeks |
| Capital costs | High ~ US$100000 per hectare | Very high ~US$250000 to US$1000000 per hectare (photobioreactor plus supporting systems) |
| Operating costs | Low (paddlewheel, $CO_2$ addition) | Higher ($CO_2$ addition, oxygen removal, cooling, cleaning, maintenance) |
| Harvesting costs | High, species dependent | Lower due to high biomass concentration and better control over species and conditions |

photobioreactor configurations available, they all have the same basic principles and parameters. The main parameter that affects photobioreactor design is provision for light penetration; that is, high surface-to-volume ratio, crucial if one wants to improve the photosynthetic efficiency. In order to achieve a high surface-to-volume ratio, several designs have been developed which can be grouped into three basic types; tubular, flat-plate and fermenter-type (Carvalho et al., 2006). Tubular and flat-plate photobioreactors are specifically designed for efficient sunlight harvesting as shown in Figures 6 and 7.

## MICROALGAE AS FEED

Microalgae contain an abundance of properties that have benefits in both animal feed and aquaculture. The growing production has seen a rise from 9.7 million tonnes in 2001 to 21 million tonnes of world aquaculture production of aquatic algae in 2011, with the African continent almost doubling its production from 0.08 million tonnes to 0.14 million tonnes in that time (FAO Fisheries and Aquaculture Department, 2013). These unicellular, but diverse organisms have a wide range of applications within the animal feed and aquaculture markets.

### Animal feed

Microalgae has shown great benefits in animal feed by providing vitamins, minerals and essential fatty acids to boost immune response; even very small amounts have proven to positively affect the animals physiology. This

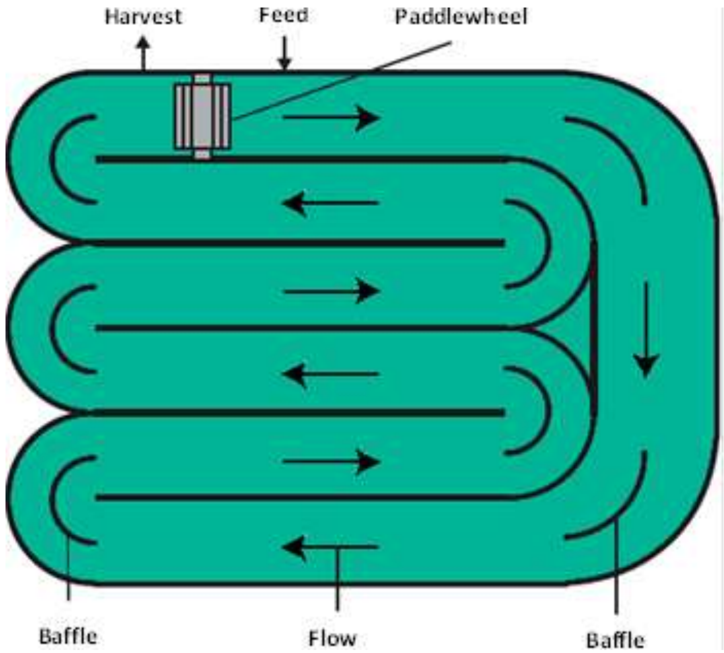


**Figure 4.** A schematic aerial view of a raceway pond (modified from Chisti, 2007).

**Figure 5.** Photograph of a 250 $m^2$ open raceway ponds (taken November 2013; Application Centre for Renewable Resources (ACRRES; Wageningen University initiative) in Lelystad).

effect also creates a shiny coat and feathers on pets (Pulz and Gross, 2004). Feed for poultry are rationed to 5 to 10% and give the yellow colour seen in broiler skin and egg yolks (Spolaore et al., 2006).

The yellow colour that microalgae can give comes from the carotenoids that they contain, of which the two most common are β-carotene and astaxanthin. Although most microalgae only contain about 1 to 2% concentration of

**Figure 6.** Photograph of a Horizontal Tubular Reactor (HTR) (taken in November 2013; AlgaePARC, Wageningen University). HTRs are composed of horizontal transparent glass or plastic (polyethylene) tubing. Gas transfer takes place in the tube connection or via a dedicated gas-exchange unit, and the angle toward sunlight is particularly adequate for efficient light harvesting (Carvalho et al., 2006).

carotenoids; species of Dunaliella can contain up to 14% β-carotene, if grown under the correct conditions. For this reason, Dunaliella species are successfully being grown on an industrial scale and sold for both animal and human use (Milledge, 2011).

### Aquaculture

Aquaculture in Africa is on the rise, with Egypt leading the race with 987 tonnes produced in 2011 (FAO Fisheries and Aquaculture Department, 2014). The global aquaculture industry rakes in billions of dollars; 2012 saw a global aquaculture production of 90.4 million tonnes worth $144.4 billion (FAO, 2014).

Microalgae are a vital component in aquaculture as they are the primary producers of the food chain, predominantly acting as a food source for larvae of molluscs, crustaceans and fish (Pulz and Gross, 2004). Just as in animal feed, microalgae are also exploited for its colouring ability such as the carotenoid astaxanthin which can pigment prawns, salmon and ornamental fish with a reddish colour. The market for this colourant alone was estimated at $200 million in 2004 costing around $2,500/kg (Spolaore et al., 2006). Unlike β-carotene, the synthetic form of astaxanthin overshadows the natural form in the market due to its high production costs (Milledge, 2011).

## MICROALGAE AS FOOD

For centuries people have been using microalgae as a food source; from China where the cyanobacteria Nostoc was used to combat famine, to another cyanobacteria Athrospira (colloquially known as Spirulina) in Chad (Kay and Barton, 1991). Despite this, it is only very, recently (the 1950's) that we began large-scale cultivation and commercial application (Spolaore et al., 2006). More than just nourishment, microalgae is now beginning to make gains in the health food sector with products like Spirulina being named as one of the greatest superfoods on Earth by the World Health Organisation (Chacón-Lee and González-Mariño, 2010). The baby food market also has potential for the inclusion of microalgae and finally it is used in therapeutic applications in HIV positive patients.

### Health supplements

Spirulina contains 60 to 70% protein per weight and are a rich source for vitamins (particularly vitamin B12 and β-carotene which is a vitamin A precursor), minerals (principally iron) and a source of dietary γ-linolenic acid (GLA) (Belay et al., 1993). Of the microalgal biomass produced annually, 75% is used for powders, tablets, capsules and pastilles; most of which are Chlorella and Spirulina. However, functional foods that contain

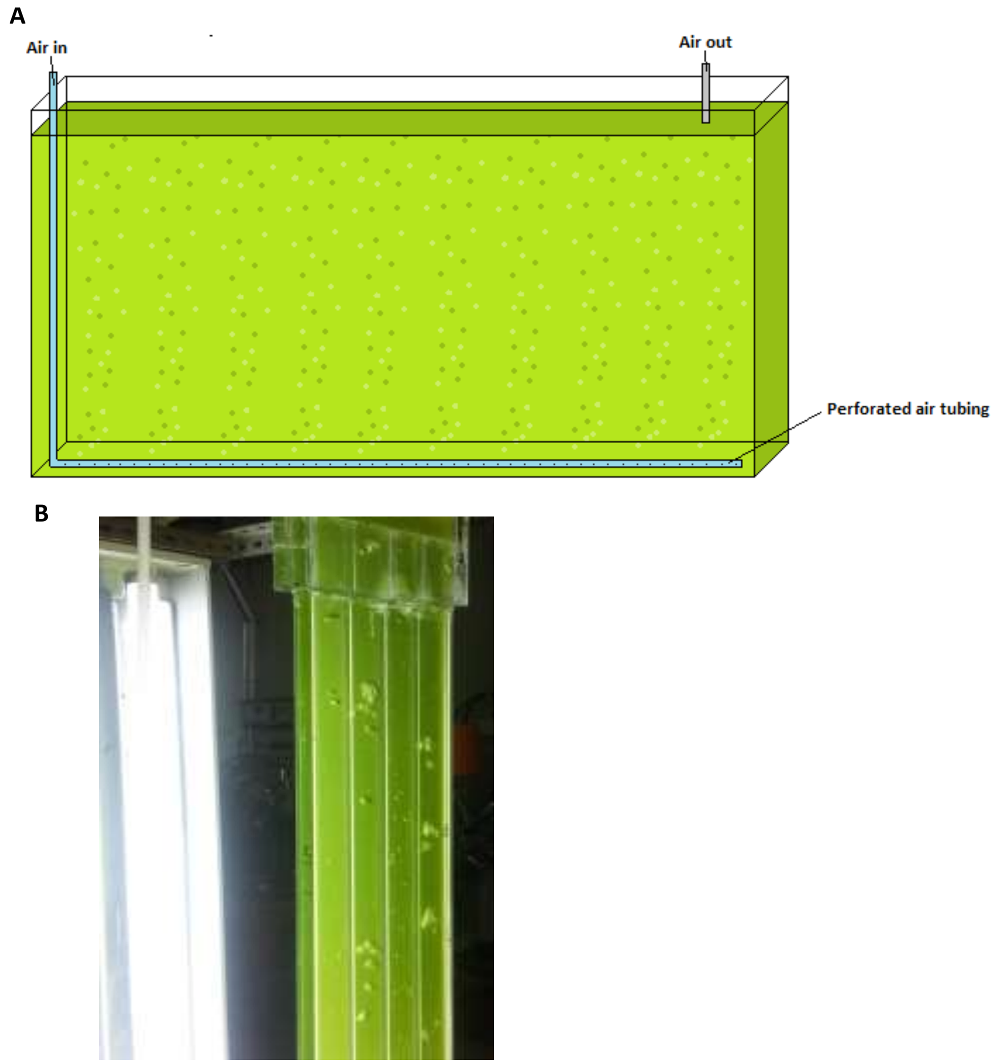


**Figure 7.** Schematic diagram of a flat-plate photobioreactor. Flat-Plate Reactors (FPRs) are designed to make efficient use of sunlight by constructing narrow panels so as to attain high area-to volume ratios **(A)**. Panels can be constructed from polyethylene bags supported by a metal framework, or from acrylic plastic walls. $CO_2$ is supplied via bubbling, which also provides mixing and the efficient removal of $0_2$. They can either be placed outside and utilize natural sunlight or be placed indoors and utilize an artificial light source. **(B)** Picture taken in November 2013, Laboratório Nacional de Energia e Geologia (LNEG), Lisbon, Portugal; schematic diagram based on designs seen at A4F AlgaeFarm).

microalgae biomass are more convenient and attractive; such as in pasta, biscuits, bread and soft drinks. Spirulina supplemented nutraceuticals as well as in pure form, have shown to support healthy intestinal bacteria such as Lactobacilli. A minimum of a 10-fold increase in growth rate of the bacteria was revealed, showing the beneficial probiotic effects of the microalgae (Pulz and Gross, 2004).

Chlorella is another key species that is produced by over 70 companies as it is a significant source for β-1,3-glucan; an active immunostimulator, free-radical scavenger and can reduce blood lipids (Spolaore et al., 2006).

The pennate marine diatom *Phaeodactylum tricornutum* has the ability to produce the poly-unsaturated fatty acids (PUFA) eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3) in high proportions of the total fatty acid content (Fajardo et al., 2007; Siron et al., 1989; Rebolloso-Fuentes et al., 2001). Marine-derived EPA and DHA, colloquially known as omega-3 PUFAs, are important in human nutrition with health benefits such as reduced cardiovascular morbidity and mortality, reduced risk of premature births and improved cognitive and behavioural development of the foetus, as well as benefiting patients with atherosclerosis, hypertension, and neurological and neuropsychiatric diseases (Yashodhara et al., 2009).

### Infant and young child feeding

In poor areas within developing countries, baby formulas are often of a low nutritional value that does not provide sufficient protein, lipid or micronutrients to the infants. Babies need adequate calories for normal and healthy development. Algae species such as Spirulina have proven to be an appropriate addition to baby food; it has the ability to help tissue growth, vision and boost the immune system (Sharoba, 2014).

More specifically, is the addition of docosahexanoic acid (DHA), a long-chain omega-3 fatty acid that is a major component in brain and visual development, allowing for improved cognitive skills and vision (Beelen et al., 2007). Higher plants and animals cannot synthesise polyunsaturated fatty acids (PUFAs) and must therefore obtain it from their food; fish and fish oils, which in turn uptake PUFAs from microalgae. Going straight to the source, microalgae bypasses the risk of accumulating toxins and smelly products. DHA occurs naturally in breast milk, but not in cow’s milk and since 1990, DHA has been recommended as an addition into infant formula (Spolaore et al., 2006).

### HIV and microalgae

Kenya has around 1.6 million people living with HIV, of which women account for about 57%. Although the country has universal testing for pregnant women, where 90% of women who attended antenatal care received their results, only half of pregnant women who were infected received antiretroviral (ARV) treatment during breastfeeding to reduce transmission risks (National AIDS Control Council (Kenya), 2014). Breastfeeding is crucial for an infant’s development and the need for ARVs in HIV infected mothers during this period is imperative to reduce mother to child transmission (Thomas et al., 2011). However, it is evident that resources and availability of ARVs could hinder this and place infants at risk. The addition of DHA from algae in infant formula could help to overcome such a barrier.

The long term use of highly active antiretroviral therapy (HAART) can lead to insulin resistance, dyslipidemia as well as weight and fat changes (Azabji-Kenfack et al., 2011a). Although dietary supplements have proven successful in the treatment of insulin resistance, the WHO states that the cheap and easily available Spirulina could be highly beneficial as it has shown to better glycaemic control, lower cholesterol and reduce blood pressure in diabetics. It was unequivocally shown in a study by Azabji-Kenfack et al. (2011b) that Spirulina drastically increased insulin sensitivity by 224.7% compared to 60% in the group using soybeans. This effect is likely due to the immune modulating effect of Spirulina, however, further study is still needed (Azabji-Kenfack et al., 2011b).

Other studies on HIV and/or severe immune deficient patients showed an increase in body weight when supplemented with Spirulina as well as increased haemoglobin levels, which in turn reduced anaemia (Azabji-Kenfack et al., 2011a).

These HIV studies therefore also shed light on the use of microalgae to tackle malnutrition, particularly in children whose development can be stunted by it. In Kenya, 35% of children under the age of 5 have stunted growth, with 42% of these children living in Kenya’s Eastern Province where they survive off a low energy maize based diet (Tomedi, 2012). These children would greatly benefit from the addition of a microalgae supplement in order to better their physical and neurological development as well as survival.

## MICROALGAE AS BIOFERTILISERS

Phosphorus (P) lies at the heart of modern agriculture as it is a major source of nutrients for plants. However, P is a finite non-renewable resource and reserves for phosphate rock could be depleted in 50 to 100 years. In fact, Morocco has a near monopoly on the reserves in Western Sahara while China has reduced exports to secure their own supply. On the other hand, the US only has about 30 years in supplies left as Western Europe and India are already completely dependent on exports. The issue is that the P is not efficiently used as it usually ends up in wastewater or as runoff into our rivers and oceans, leading to toxic algal blooms (Cordell et al., 2009).

Globally, humans physically consume about 3 tonnes of P and since virtually 100% of consumed P is excreted, the same 3 tonnes finds its way out into our wastewater. Usually this would then be removed via waterways. Currently, only 10% of human excreta is intentionally or unintentionally recirculated, however urban sites can be considered P hotspots and be exploited to better recycle the finite resource (Cordell et al., 2009).

Microalgae have the unique capacity for ‘luxury P uptake’; essentially they can sequester high amounts of P. Wastewater has an excess of P that can be efficiently utilised in microalgal growth. This simple idea is used in small communities globally to treat local wastewater systems (Powell and Shilton, 2008), however, this can then be taken a step further by employing this microalgae as a biofertiliser.

## BIOFUELS

Biofuels are generally divided into “first-generation” and “second-generation” biofuels, with microalgal-based

**Table 2.** Comparison of some sources of biodiesel (from Chisti, 2007).

| Crop | Oil palm (L/ha) | Land area needed (M ha)[a] |
|---|---|---|
| Corn | 172 | 1540 |
| Soybean | 446 | 594 |
| canola | 1190 | 223 |
| jatropha | 1892 | 140 |
| coconut | 2689 | 99 |
| Oil palm | 5950 | 45 |
| microalgae[b] | 136900 | 2 |
| Microalgae[c] | 58700 | 4.5 |

[a] For meeting 50% of all transport fuel needs of the United States; [b] 70% oil (by wt) in biomass; [c] 30% oil (by wt) in biomass.

biofuels considered "third-generation". Any biofuel production process which can successfully replace an equivalent conventional fuel needs to fulfil three basic requirements. First, a sufficient feedstock to produce fuel at a commercial scale should be produced, secondly it should cost less than conventional fossil fuel, and thirdly, it should match standard specification of fuel quality (Singh and Gu, 2010).

First-generation biofuels are generally the product of the often edible and above-ground biomass (usually sugars, grains or seeds) produced by crop feedstock, and relatively simple processing of the biomass is required to produce a finished fuel (Naik et al., 2010). Second-generation biofuels are produced from biomass in a more sustainable fashion, which is truly carbon neutral or even carbon negative in terms of its impact on $CO_2$ concentrations (Gomez et al., 2008). The biomass utilised is known as lignocellulosic (LC) biomass, and makes up the majority of the cheap and abundant non-food materials available from plants, including residues of forest management or food crop production (such as corn stalks or rice husks) or whole plant biomass, such as grasses or trees grown specifically for biofuel purposes (Naik et al., 2010).

Microalgae derived biofuels have three major advantages over first and second-generation biofuels; overcoming food-versus-fuel predicament, a higher potential biofuel yield per hectare and the ability to be harvested throughout most of the year, thus giving a regular supply of biomass (Table 2) (Chisti, 2007, 2008).

However, as it stands, microalgal-derived biofuels are not a commercial reality simply because they are not economically feasible. The cost of production and thus the market price of algal biofuels simply cannot compete with the comparably low cost of fossil fuel prices (Norsker et al., 2011).

## The food-versus-fuel predicament

In a country such as Kenya, food security remains a major issue and therefore using crops as a source of biomass for biofuel is not feasible. The ability for microalgae to use non-arable land is another characteristic that makes it so favourable as a biofuel source; Kenya has 45.8% non-arable land that would not compete with land needed for food crops (CIA, 2016). In 2009, Bedford Biofuels, a Canadian company, began talks with local ranch owners in Kenya's Tana Delta District on establishing a large Jatropha plantation. However, they were met with resistance by local NGOs even though the project could have brought in international investment and secured jobs for the local community. A year after planting the first seedlings their operations were closed down and the company filed for bankruptcy in 2013. The collapse of the project was down to a combination of an 'anti-BB' campaign by NGOs, local residents who were afraid of eviction or losing access to grazing land and the eruption of ethnic violence (Krijtenburg and Evers, 2014). Fortunately, microalgae cultivation would not face the same issues as it will not take up grazing or arable land therefore reducing the resistance from both local NGOs and residents.

## Theoretical maximum annual average lipid yields

A study carried out by Moody et al. (2014) used large-scale, validated, outdoor photobioreactor microalgae growth model based on 21 reactor- and species-specific inputs to model the growth of Nannochloropsis. The model accurately accounts for biological effects such as nutrient uptake, respiration, and temperature and uses hourly historical meteorological data to determine the current global productivity potential. Table 3 contains the results of the model in terms of average microalgae lipid yields from various regions around the world and shows that Kisumu, a city in the west of Kenya, would be the optimal location for cultivation of the microalgae Nannochloropsis in an outdoor bioreactor.

## CONCLUSION

Geographically speaking, Kenya is an ideal location for

**Table 3.** Average microalgae lipid yields in cubic metres per hectare$^{-1}$ per metre$^{-1}$ (corresponding biomass yields in grams per metre$^{-1}$ per day$^{-1}$) of various regions around the world with respective high and low monthly lipid yields (Moody et al., 2014).

| Location | Maximum monthly | Average monthly | Lowest monthly |
|---|---|---|---|
| Kisumu, Kenya | 2.47 (15.6) | 2.28 (14.8) | 2.07 (13.3) |
| Learmonth, Australia | 2.61 (18.0) | 2.16 (14.0) | 1.49 (9.64) |
| Trivandrum, India | 2.42 (15.6) | 2.08 (13.4) | 1.75 (11.3) |
| Cali, Columbia | 2.27 (14.6) | 2.04 (13.2) | .1.91 (12.3) |
| Hawaii, United States | 2.36 (15.3) | 1.97 (12.8) | 1.50 (9.95) |
| Yuma, AZ, United States | 2.68 (17.3) | 1.80 (11.7) | 0.68 (5.16) |
| Poltavka, Russia | 2.30 (14.1) | 1.06 (6.84) | 0.46 (2.23) |
| Bagaskar, Finland | 2.19 (14.1) | 0.77 (5.00) | 0.55 (3.86) |
| Punta Arenas, Chila | 1.77 (11.9) | 0.77 (5.07) | 0.51 (3.25) |

culturing algae as it lies on the equator and therefore receives optimum light and temperature for high yields. Moreover, the Kenyan government has also set out a development policy termed 'Kenya Vision 2030' that aims to transform the nation into a newly industrialised country with a high quality of life for all its people by the year 2030 (http://www.vision2030.go.ke/). Microalgae have the capability to fulfil some of the Kenya Vision 2030 goals.

Native Spirulina is already being successfully cultured in Kisumu, Kenya by a company called Dunga Spirulina that sell the microalgae as a health supplement and to NGOs to support those with HIV (http://www.dungaspirulina.com/). The Kenyan government aims to enhance locally derived natural health products and the natural products industry. Using Dunga Spirulina as a small success, it is evident that high value products such as β-carotene and astaxanthin could be sold, and even exported, as colourants, animal feed, health food supplements and aquaculture in Kenya. As a healthy food source, microalgae could also have an impact in combating hunger, HIV and reducing child mortality; 3 of the 8 Millennium Development Goals (UN, 2015). Infant formula supplemented with DHA from microalgae allows for a more nutrient rich formula, necessary for healthy development. Furthermore, this principle would aid mothers with the HIV virus who are unable to access ARVs to avoid breastfeeding, thus reducing mother to child transmission. Using this natural product would also serve to treat malnourishment in Kenya, an aspect that could in turn help individuals to fight off infection of other diseases prevalent in the region.

The Kenya Vision 2030 also aims to make fertilisers more affordable and accessible to further increase their agriculture as low rates in sub-saharan Africa mean 75% of the soils are nutrient deficient; the irony is that Africa is the biggest phosphate rock export, but has the greatest food shortages. Kenya Vision 2030 also aims to reduce solid waste and pollution is urban areas, and by utilising microalgae in wastewater management, they can tackle these goals simultaneously; recycling the finite resource, phosphorus, by culturing microalgae in wastewater and then using the biomass in fertilisers.

For the Kenyan people, particularly those in rural communities, sustainable developments such as culturing microalgae will offer a world of opportunity. Beyond health and economic benefits, microalgae farms would offer employment, particularly for low-skilled jobs. This would in turn improve their quality of life as they would be able to improve housing and education opportunities for their families. However, an important aspect would be to promote employment for women due to persistent gender-based inequalities in most developing countries (Rossi and Lambrou, 2009), another of the Millennium Development Goals. These sustainable microalgae developments could allow for rural communities to work together to attain, a food source, biofertiliser, health supplement and the opportunity to generate income from jobs and high-value products. All this could be possible thanks to tiny, microscopic algae.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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