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# Algae for a Second Green Revolution

## Executive summary

Back in the forties of the last century, the Mexican Ministry of Agriculture joined forces with the Rockefeller and Ford Foundations and got involved in agriculture research which resulted in a near doubling of wheat yields in countries such as Mexico, Pakistan and India. This revolution in agricultural sciences became known as the Green Revolution and it has provided the world with food the past seventy years. According to the Food and Agricultural Organization of the United Nations (FAO) the world's total 'food bill' amounts to 1,019 billion USD of market value per year.

In 2008 the world's population counted 6.8 billion people and the United Nations predict that by 2030 the human population will have increased up to an estimated 8.2 billion individuals. This presents humankind with a set of unprecedented challenges regarding food and feed production, but also concerning safe drinking water and affordable energy sources.

Today, the Aquaculture sector is promoting itself as the industry that, with a Blue Revolution, will create the next basis of the world food production by growing fish and other aquatic animals. With the new scientific findings and industrial production techniques, the aquaculture industry may indeed successfully meet this challenge.

However, the underlying real challenge which both agriculture and aquaculture will have to meet is the one of true sustainability. Both industries will have to build on sustainable resources and feedstock to produce feed for fish and live stock. But especially our continued energy supply will have to be based on a sustainable feedstock. The recent crisis in animal feedstock, in part as a result of the increased demand for bio-fuels, has made it very clear that there is in fact fairly little room left to further increase land based food production. We are increasingly being confronted by the limits of available agricultural lands and reliable freshwater as well as having to deal with volatile energy costs.

Thus, there is an urgent need for new sustainable resources to produce food for a growing population and feed for fish and live stock. This has to be achieved independently of the use of freshwater and with sustainable energy sources. This need is not trivial and can only be filled by a Second Green Revolution.

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The answer to all three issues, food, freshwater and energy lies in large scale production of micro-algae. The next green revolution will be based on the industrial production of micro-algae. Why? Because micro-algae produce ten times more biomass than any terrestrial crop. More importantly, micro-algae can be grown in ocean water, using waste nutrients, simultaneously producing food, feed and energy while reducing Green House Gas (GHG) emissions.

The scientific findings and especially the industrial production processes that have thus far accumulated make the Second Green Revolution through micro-algae already a realistic possibility. Now is the time for us to export this Second Green Revolution to all the nations over the world.

Depending on the micro-algal species and ecological group there are various ways to produce micro-algae. One method that was developed in the past decade focuses on attached diatom algae. In its industrialized format it is referred to as the DIAFORCE™ platform. Diatom farms based on this platform are fully operational at pre-industrial scale for some time now. It has been shown that these farms can produce 100 to 150 ton/ha year. The resulting algal biomass can contain up to 20-30 % of triglyceride storage oil. The production technology is available and industrially scalable.

Even more importantly, there is an economic reality behind the industrial scaling. The basics of the business models for the algae industry have been unveiled. Applying these insights on the business case for DIAFORCE ™ farms shows that diatom oil for bio-fuel can be produced at prices of $50-$150/bbl. The two drivers that make this possible are sufficient scaling and achieving maximal commercial value of the residual diatom meal. Diatom meal has substantial nutritional value for human and animal. In fact diatoms form the basis of the ocean food chains and webs. This tremendous nutritional value can be translated into real business in several markets, both human and animal. Diatom oil for bio-fuel purposes should in fact be considered as a by-product.

Although feeding the people of the world is by itself a very admirable motivator, history has taught us that it will be the solid economic models that will ultimately be the key drivers of the second green revolution. The second green revolution will not be construed on an academic desk but will rise up from the international trade floors and from algae-culturing farms worldwide. With diatom algae driving this next sustainable industry it appears that human and economical benefits may coincide.

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# The Second Green Revolution

## The demographic explosion

Never before in the history of mankind have as many people been alive as today. In 2008 the world's population counted 6.8 billion people. According to the United Nations by 2030 the human population will have increased up to an estimated 8.2 billion individuals. At the present consumption rate this means that we will have to find an additional 80,000 to 175,000 $mi^2$ of agricultural land for grain production alone. For comparison, this area is of a size that lies somewhere between the respective land surfaces of the states North Dakota, USA or the province Karnataka, India and the countries Paraguay or Sweden.

Although the figures are new and staggeringly high, we have been in this situation before.

Throughout history there are numerous accounts of huge and devastating famines decimating entire regions. Even as recent as at the beginning of the twentieth century, regularly occurring massive famines were considered as a natural part of the human ecology. This was true in various regions of the world, for instance the Indian peninsula.

Things changed dramatically when, back in the forties of last century, the Mexican Ministry of Agriculture joined forces with the respective Rockefeller and Ford Foundations and got involved in agriculture research. This joint effort resulted in a near doubling of wheat yields in countries such as Mexico, Pakistan and India. New rice varieties, such as the so called 'Miracle Rice', yielded crops of more than 5 times that of traditional rice.

This revolution in agricultural sciences became known as the Green Revolution and it has provided the world with food these past seventy years. This Green Revolution has also created an economical dimension of unseen size. An immense economic fabric of international trading has since come into place and, according to the FAO (2008), the world's total 'food bill' amounts to 1,019 billion USD of market value per year.

Since the beginning of the Green Revolution the human population has increased by an additional 4 billion people. Those are 4 billion people with an ever increasing need for reliable food supplies and safe drinking water as well as the wish for reasonable living conditions. By 2030 an additional 1.5 to 2.0 billion people will be here with the same needs or even more so. The Green Revolution is nearing its limits to what it can do to support these additional people.

In addition to the growing demand for food and feed, we are also confronted with the rapidly approaching end of another limited resource, petroleum. ‘Peak Oil’ is the moment in time when the maximum capacity of petroleum extraction is reached, after which global production will inevitably decline. Peak oil was predicted by Hubbert in 1956 and was reached in the USA around 1970. Since then oil production is in decline for 33 of the 48 important oil producing countries (Worldwatch 2005).

Regardless whether global Peak Oil is here today or somewhere during the next few years, we are truly nearing the end of the fossil fuel era. The Hirsh Report stated that global Peak Oil presents us with an ‘unprecedented risk management problem’ of which the economic, social and political costs will be enormous (US Department of Energy (USDE) 2005). Timely action was deemed imperative to implement mitigation solutions and prevent severe and disruptive consequences. We may not have been as pro-active as we should have been.

However, quite a number of well intended actions may only bring us temporary alleviation. It would appear that the increasing human population has finally caught up with the limited reserves of fossil fuel. As the Green Revolution relies heavily on cheap fossil fuel for fertilizers, pesticides and herbicides and on freshwater for irrigation purposes, we cannot fall back on known agricultural solutions. The challenge this time round is threefold, namely food, freshwater and fuel, all combined and intimately linked to each other. Of course, we can resort to agriculture to resolve some of the nearest fuel problems but we must realize that this will only tide us over for a very short time. The recent crisis in animal feedstock, in part as a result of the increased use for bio-fuels, has made this very clear. There is limited room left to increase the production of land based food and fuel resources building on the First Green Revolution. We must start looking elsewhere for solutions.

## Micro-algae

By now it is clear to all that the present day situation is a serious one. But humankind has met with serious situations before. By using our ingenuity we have always met these challenges with success and turned seemingly insurmountable challenges into unseen opportunities. And again there now are viable solutions at hand and - even more importantly - these solutions are sustainable and can help us overcome the production limitations of today with a long term perspective.

So there is no need for panic, although there is no time to lose either.

First of all, let it be clear that we are not using Earth’s resources efficiently. In fact, a huge part of the available resources are not used at all, or only marginally so. While about 70% of the world’s available freshwater is used for modern agriculture, more than half of which in an unsustainable fashion, more than 97% of the world’s water supply remains unused. The oceans were the cradle of all life on earth and form the basis of the world’s fisheries and aquaculture. There are enormous tracts of the oceans that are exceptionally fertile and productive and that are fairly easily accessible. We have all the production area that we could possibly need. We just never really thought of it that way.

We already have the skills to use these untapped resources. True, about two thirds of the 150 million tons of annual marine production today consists of simple capture of naturally growing creatures. But much like the first Green Revolution consisted of exporting existing agricultural techniques to the entire world, equally so we find that most of the required techniques to farm the oceans sustainably are readily available. Some techniques have been around for many centuries, while some were developed during the past decades. All of which are fully operational and ready to expand.

The second Green Revolution consists of the industrial cultivation of micro-algae. The answer to all three issues: food, freshwater and energy lies in large scale production of micro-algae. In the decades to come, we will see new crops from previously little known plants and animals, we will learn to eat remarkable food and strange new dishes like in Jules Verne's book "20,000 Leagues under the Sea", and there will be international and maritime legal and regulatory issues to be settled. In short we will have sustainable energy and sufficient food for the people of the earth.

What are micro-algae? Micro-algae are single celled plants that naturally grow in water. Oceans obviously come to mind, but actually any location with even the smallest amount of water harbors micro-algae. Such locations can range from deserts where we find algae in a single dew drop in the Mojave Desert to ice floes in the Antarctic seas inside which the ice algae thrive. They are incredibly diverse with over an estimated 250,000 species of them.

Micro-algae produce ten to twenty times more biomass per unit area than any terrestrial crop. More importantly, micro-algae can be grown in ocean water, while using waste nutrients and at the same time reducing greenhouse gas (GHG) emissions. They can be grown directly in the oceans or in seawater on wastelands and deserts. Micro-algal biomass is to be considered an entirely new raw material which can be used as food, feed or fuel.

This productivity may seem miraculous but in fact it isn't. Micro-algae are single celled plants and therefore are sometimes considered primitive. That notion is quite incorrect. Micro-algae are highly evolved and through the ages have become very efficient. Being single celled, they do not invest in structural tissues like roots and stems that contribute little to the overall reproduction of a plant. Micro-algae invest all the energy and nutrients they gather only in fully functioning cells. Every single algal cell is complete and self sufficient. All they have to do is divide into more complete, functioning cells. They therefore reproduce rapidly and the resulting biomass is a complete and highly nutritious resource for us to harvest. For comparison, imagine that a single corn grain could directly divide into more corn grains without the annoying intermediate step of having to grow into a plant. Wouldn't that be a green revolution?

So if micro-algae are so incredible why haven't we heard of them before?

Micro-algae have been part of the human diet for thousands of years, They are traditionally known as 'tecuitlatl' in South America, as 'dihe' in Africa and 'iwatake' or 'seogi' in Asia. They were however not intentionally cultivated but rather gathered from natural sources. Growing micro-algae using modern techniques has been around for only 150 years. Although micro-algae had been studied for some time, the first scientifically investigated algae species belonged to the genus *Chlorella*. It was isolated by the Dutch scientist Beijerinck (figure right) at the end of the 19th century and was then 'scientifically grown' in the laboratory. At the beginning of the twentieth century a number of sophisticated cultivation and breeding experiments were successfully performed by people such as Von Stosh and Geitler. By the med-century the first large scale pilot plants were undergoing their trial runs in the US, Japan and Europe. In fact, micro-algae were proposed as one of the possible solutions to alleviate the famines still ravaging the human populations (Burlew 1952). Back then terrestrial crops won the day but maybe for no other reason than the timing of the joint effort of the Mexican government and the Rockefeller and Ford Foundations.

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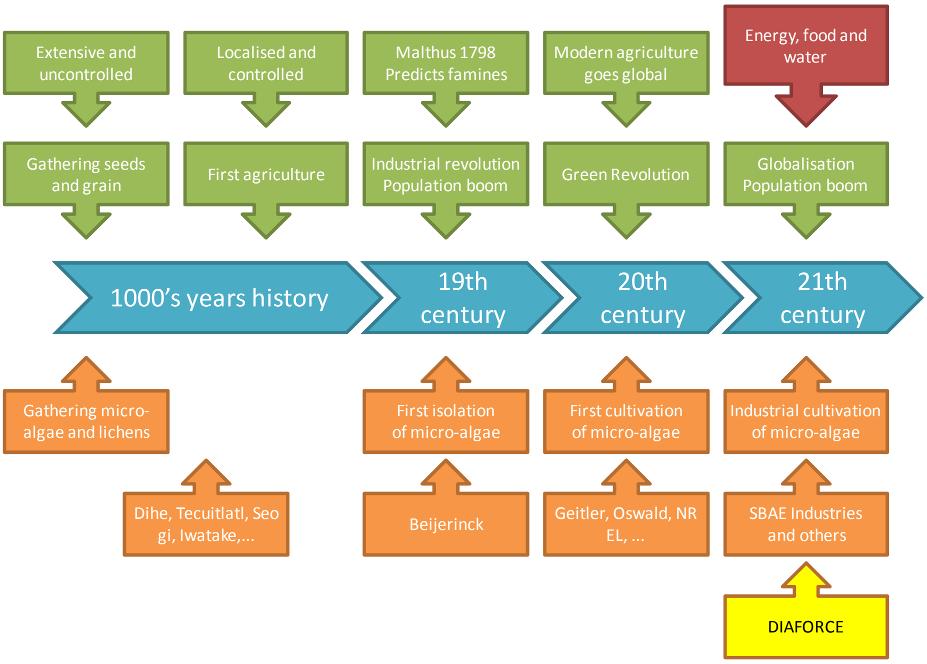
During the seventies and eighties micro-algae were further investigated for their potential applications as bio-fuel feedstock. An example is the US Aquatic Species Project (NREL USDE, Sheehan 1996).

Today micro-algae are used either directly as food, feed, nutraceuticals or additives or as derived products such as cosmetic and pharmaceutical ingredients. So, micro-algae are by no means a newfangled 'flavor of the month' chasing industrial investors and government funding agencies. There is an active micro-algae market out there that is doing very well and is growing rapidly.

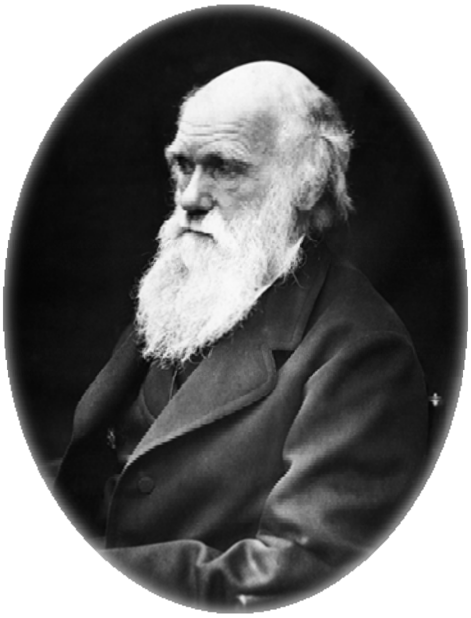
The Second Green Revolution is the logical consequence of almost 150 years of scientific research, applied engineering, economical analyses and industrial roll out. Industrial production of micro-algae did not come out of nowhere. It is here to stay and it has all that is required to grow into a multi-billion dollar industry.

## Breeding for better food




There are many parallels between the history of agriculture and that of the cultivation of micro-algae. Then again, history tends to repeat itself. Thousands of years ago we gathered seeds and grains from wild plants, much later we started cultivating them in a more systematic way. In the course of time we got breeding of plants and animals down to a fine art and this provided us with the initial evidence to substantiate the mechanisms of Darwin’s theory of evolution by natural selection (1859 1st Ed.). The mechanisms behind the breeding strategies were discovered by Gregor Mendel, the father of genetica, and published in 1866.

Last century we had the Green Revolution with which the modern techniques and naturally enhanced plant varieties were exported worldwide. We can go through this process much faster now because a lot of the insights and techniques we already have can be translated towards the mass cultivation of micro-algae. There are also a number of obviously different challenges in both biology and technology. A lot needed to be learned and experienced during the past couple of decades. Especially during the past 10 to 15 years most of the essential pieces of both scientific knowledge and applied engineering came together to form one consistent and complete picture. Further down the line, it is highly likely that structural breeding programs using natural processes will be implemented for micro-algae during the next decade.



Charles Darwin in 1869 (leftà) Gregor Mendel (Right)

## Diatoms

Micro-algae are a very diverse set of organisms and are typically divided into roughly twelve major groups. To give you an idea, there is more difference between the species of any two of these groups than there is between us and a kangaroo. One of these groups is the group called Diatoms (Bacillariophyta). These micro-algae are mostly unicellular but can occur in colonies. They live in freshwater, brackish water and marine systems all over the world. Their most striking feature is their unique cell wall which is made of hydrated silica. Diatoms live in glass houses.

Diatoms are very productive and are considered to account for about one third of the world's primary production (measured as plant biomass) and to generate about 50% of the world's oxygen. They are to a large extent the green lungs of the earth. They produce oil (lipids) as both structural and storage molecules. They are highly nutritious and form the starting point of the food chains in the oceans. They are rich in essential fatty acids (oils), energy molecules (triglycerides) and essential amino acids. They produce massively in the oceans and, what hasn't been eaten by fish or other marine life, settles to the bottom of the oceans. Over the past millions of years a lot of these sinking diatoms have accumulated and a substantial part of the petroleum reserves consist of fossilized diatom biomass.

Why are they so successful? The answer in part lies in the use of hydrated silica for the cell walls. This is substantially different from most other algae who build their cell walls from organic carbons like cellulose and hemi-cellulose. Depositing silica in structural forms requires only about 6.5 % of the energy required to synthesize cell walls made from carbohydrates (Raven 1983). This leaves a substantial amount of excess energy that the diatoms can now use for useful metabolic purposes such as growth and reproduction. It has been suggested that the silica (or glass) through its beneficial optical properties conveys light more efficiently towards the interior of the diatom cell (Becker 1996).

In addition, Diatoms have evolved their own pigments, such as fucoxanthin. These pigments enable them to capture extra energy from sunlight in the range of 450 to 540 nm wave length and peaking at 510-525 nm. They can 'harvest' a larger portion of the light spectrum and do so at lower intensities. This is one of the biological mechanisms that enable them to be the very first of all micro-algae to flourish after the dark winter months and then continue to be productive during late autumn.

The combination of silica biology and efficient pigments results in a substantial energetic competitive advantage that diatoms have over their fellow micro-algae. The advantage of diatoms is as effective as it is simple: capture more sunlight energy and use this energy more efficiently to produce more cells. As a result some diatoms can divide up to three and sometimes four times per day. It is no wonder they have become one of the most diverse and abundant groups of algae.

Diatoms and their production potential have not gone unnoticed. Because of their exceptional productivity and oil properties, diatoms were proposed as one of the more interesting groups of micro-algae that needed further development, for instance towards biofuel applications (NREL US DOE 1996).

## How to grow micro-algae?

There are a few ways to grow micro-algae. The appropriate method for any particular species or group largely depends on the particular environment they naturally inhabit. There are two distinct types of micro-algal environment that can be recognized. There is the 'open water' type in which the planktonic or free floating algae are found suspended in the water and the 'ocean floors and river banks' type in which the peri-fyton, or attached algae are found clinging to rocks and plants.

These very different environments have resulted in very different life strategies that the various micro-algae have developed. Thus, planktonic algae float freely in the water, while the attached ones are stuck on rocks, pebbles and plants. This major division in life strategies can be found in every algal group. Obviously, growing the respective micro-algae requires different cultivation techniques.

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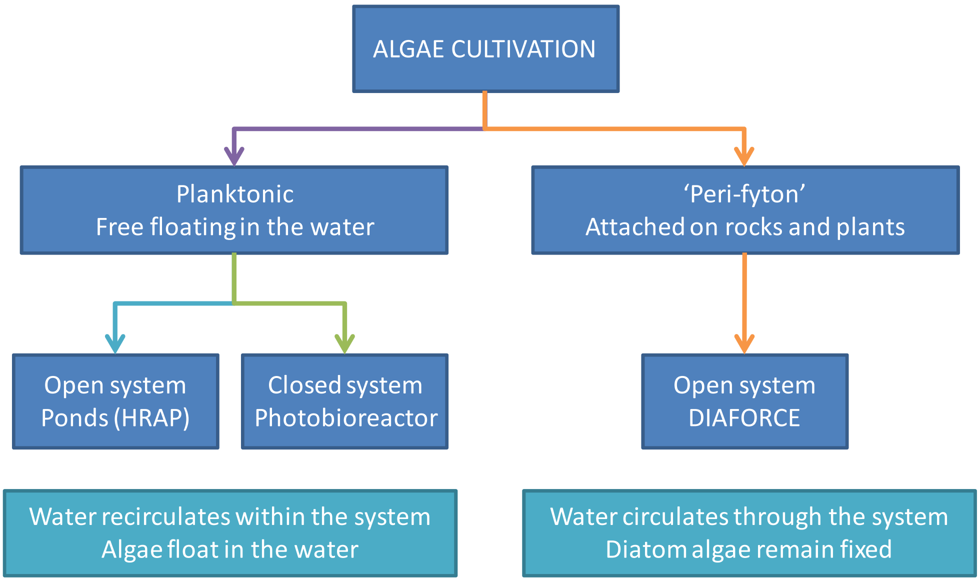


The first cultivation techniques were based on the scientific experience gathered at the beginning of the twentieth century. This just happened to be a *Chlorella* species, a free floating planktonic micro-alga. As a result virtually all of the cultivation technologies that were developed during the 20$^{th}$ century are focused on growing algae with a planktonic life strategy. A number of problems had to be solved and two major methodologies have emerged. On the one hand, there are the open systems such as ponds and runway systems (e.g. HRAP – High Rate Algal Pond systems) while on the other hand there are the closed systems (PBRs – Photo Bio Reactors) of various types and designs. Both methods are tried and tested and as with any technology each has its advantages and disadvantages. Both however have resulted in established industrial production processes with dozens of commercial companies worldwide. It is estimated that the present day market of micro-algae represents an annual value of between 750 to 1,000 million USD. By now it should be clear that micro-algae are no strangers to us and they are economically very real.

The planktonic production methodologies have one common drawback when it comes to mass production for food, feed and fuel. As is usually the case with bulk production the limitations lie in the economics of the system. The cost of the algae produced in planktonic systems only allows the algae to be used for high value applications and for which premium prices are readily paid. At production costs of $4.50-$45.00 /pound depending on the species, it is difficult to go for bulk production, especially for fuel. For bulk production other methods had to be devised.

Various detailed analyses of the planktonic methods have already clearly identified the major cost drivers that result in the prohibitive costs (e.g. NREL USDE). The main issues are: stability of the increased productivity, economical harvesting, downstream processing and industrial scaling. Upon examination of the cost-drivers one quickly realizes that they can be avoided to a large extent by focusing on the other group of algae, the attached micro-algae or peri-fyton.

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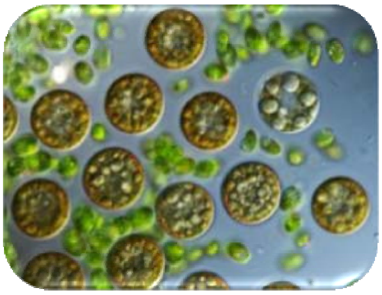
# The DIAFORCE™ platform



DIAFORCE™ literally means 'the strength of diatoms'. A first step into cost reduction is increasing the biological productivity per production unit. Production can immediately be improved by selecting one of the most productive micro-algal groups of all, namely diatoms. But it is not just a simple matter of choosing the diatoms that give the DIAFORCE™ platform its economic strength. A well defined set of properties and conditions can be discerned within the DIAFORCE's patented approach. The system reduces production costs in the harvest phase and in the downstream processes by almost two orders of magnitude.

The system imitates nature. It imitates a stream, or a tidal zone, in which the water is continuously moving while the micro-algae remain in place, attached to some rock or plant. This very active and hydro-dynamically stressing environment has evolutionary driven the resident diatom species to become very fast growing. Among the already proliferative diatoms, these are the most productive species. The DIAFORCE ™ is an engineered system that doesn't use rocks or plants for attachment of the diatoms but instead uses specially designed artificial carriers that are placed in the water stream and upon which the diatoms grow.

The system uses poly-cultures of multiple species. While optimized mono-cultivation of single plant varieties was one of the key elements of the first Green Revolution, agronomists have known for decades that a diverse tropical rainforest is far more productive than any single modern crop. Diversity is not just some fancy word; it is a powerful tool that can be used to increase productivity. Poly cultures have many advantages, and one key advantage is that poly-cultivation allows efficient use of resources. While the technique of mono-cultivation results in the very efficient use of the individual species that is grown, it is not very efficient in using the total available environment and all the associated resources. For instance, runoff fertilizers are by definition a sunk cost as they are not incorporated into biomass. Furthermore they create additional burdens and even hidden costs in their disrupting effects on the environment as a whole and the ecosystem services this supports. Poly-cultures use all these nutrients as efficiently as possible which ultimately results in more useful biomass.

DIAFORCE ™ is therefore an ecosystem approach. This means that it uses the existing laws of nature and all the available resources to grow diatoms. The DIAFORCE ™ poly-culture is not just a set of species randomly thrown together in a laboratory, but it is a balanced and naturally evolved community. The DIAFORCE system specifically grows poly-cultures that are composed of those species that naturally occur in local rivers or tidal zones. The micro-algae are grown in a community of multiple species on site. This directly results in increased productivity and improved stability. Upon startup of a new DIAFORCE ™ system a poly-culture is allowed to adapt to the DIAFORCE system and as such autonomously to change its species composition from the beginning onward. The longer a system runs the more robust and productive it becomes. Through its robustness, the poly-culture is self-inoculating and thus fully regenerating. There is no start/stop scenario nor are there switching costs for new crops in the DIAFORCE. The poly-culture can continue to live on.

As productivity is a function of incident solar irradiation the yield per unit area varies with the position of a DIAFORCE ™ system on the planet. The yield of a DIAFORCE system in sunny temperate climates ranges between 40 to 60 tons/acre/year (dry weight).

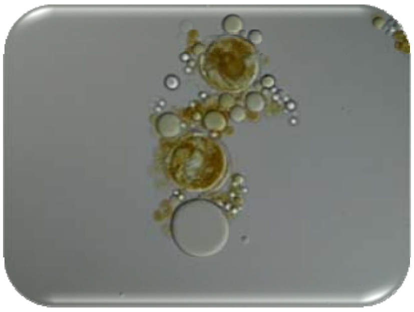
The system is highly modular. The community biology of the poly-culture is always productive and fully functional anywhere in the system which means that once the nourishing water stream is running the DIAFORCE ™ can easily be extended. This is similar to the life in a river which runs until it reaches the ocean. The modularity consists of multiple channels laying alongside each other, as if a set of rivers are laying adjacent to each other. The system functions equally well with freshwater, seawater and even brackish water.

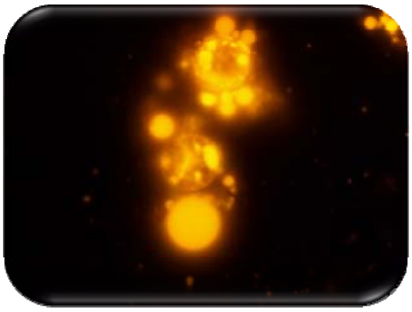
In short, the DIAFORCE system endlessly generates diatoms in a community configuration and the biomass is conveniently attached to carriers. Harvesting, which typically is a significant cost in planktonic systems, is achieved by simply lifting the carriers covered with the diatoms out of the water stream. The diatoms are subsequently easily removed from the carriers which are then placed back in the water stream and the harvested diatoms are further processed. Compared to conventional systems this method of harvesting automatically reduces the water to be processed by over 95%.

## Poly-modulation™ and extraction

Diatom algae have some very interesting properties. One of these is their ability to accumulate large amounts of oil (lipids) as energy storage inside their cells. These lipids are triglycerides and typically consist of C 14-C 16 fatty acids. Inducing sufficient oil accumulation at industrial scale however requires specific engineering. This is what is called the Poly-Modulation™ technology.

Poly-modulation enables the induction of oil accumulation in diatoms in large scale systems. This typically increases triglyceride content up to 20-30%. These oils are not structurally integrated into the cells but are in liquid form present in discrete pockets inside the diatom cell. As such they are easily separated from the rest of the cell content by conventional methods of liquid-solid phase separation.





The triglycerides in diatoms are liquid oils (left picture). The Nile red dye highlights (right picture) the neutral lipids in triglyceride form under fluorescence microscope and not the structural phospholipids.

Extraction of this oil is relatively easy in comparison with traditional micro-algae. Typical cell walls of green algae are flexible and impermeable. It is very difficult to open the cell wall of traditional algae. They are often compared to rubber balls bouncing off the walls. To make things even more challenging carbohydrate cell walls are also very resistant to solvents.

It is again the silica biology that allows the use of tried and tested engineering principles. Diatom cell walls are made of silica and are therefore solid and hard. Furthermore, the diatom cell walls consist of two separate parts between which there is a seam. This seam can be easily opened by applying the appropriate mechanical forces after which the liquid oil is released from the cells.

Moreover the silica cell walls are perforated by hundreds of tiny openings through which the diatom interacts with the environment. Through these perforations the extraction solvents permeate through the cell walls and thus access the oil inside the diatom biomass. The picture of the fluorescent diatom illustrates the permeability of diatom cell walls. The Nile red coloration was initially developed for diatoms and readily highlights intracellular liquid triglycerides (ASP NREL 1996).

## Economic model

The industrial production of diatoms or other micro-algae, and the success of the Second Green Revolution will depend on the design of new business models. Sustainable production allows for sustainable economics. To attain economic viability the business model should achieve the maximum commercial value of the entire biomass. Indeed, the key lies in obtaining the maximum value of all of the produced diatom biomass. Imagine a diatom farm of 250 acres. In temperate sunny regions this would produce say around 12,000 tons/year of total biomass. With the poly-modulation technology this would contain about 20-30% of triglyceride oil. The net yield would be around 3,000 tons of triglyceride oil and 9,000 tons of algal biomass.

This residual biomass can be commercialized as a highly nutritious protein meal, loaded with residual essential fatty acids (omega 3's), anti-oxidants, vitamins, trace elements and phytosterols. Commercialisation of this diatom meal at about $2.25-$4.50/pound allows for the diatom oil to be sold profitably at $50-$100/barrel. If the diatom business case is to succeed, the value of both the diatom oil and the diatom meal are inseparably intertwined. Both must be present in the business proposal from day one. Economic realization of the total biomass is imperative for any 'algae to fuel' business proposal.

The logic is fairly straightforward. Because petroleum, the fossil fuel, has no real production costs, diatom oil should become maximally insensitive to the production cost of the total diatom biomass. Once this is the case, then diatom oil becomes competitive in the present day market situation and can play a substantial role in the energy industry. This is achieved by allocating most or all of the production costs of the total biomass to the commercialization of the residual diatom meal. Consequently the COGS of the diatom oil drops to near zero and the price per barrel diatom oil can be determined based on other external market drivers.

Obviously, such a model becomes stronger through economies of scale. Therefore, to produce diatom oil at prices competitive with fuel, the diatom production capacity must be sufficiently scaled. Given sufficient volume the diatom meal will become an important product on the marketplace. The large volumes generate a sufficiently large turnover to carry the full production cost. This raises the crucial question of the value of the diatom meal.

When it comes to the value of the residual algal biomass a lot of prices are going back and forth in algae world. It is important to get a few facts straight. First, one should realize that there is no such thing as the bulk algae market place. There are as yet no established or generally accepted rules or mechanisms to determine the value of bulk algal biomass. Almost everybody that engages into the algae business comes from another sector, and many simply impose the rules and principles of their own 'home-market' on the algae biomass. These 'foreign' methodologies of course need factual input to determine a value, for instance protein content. For various sectors these methodologies have been formalized and are readily available in software packages. These are typically 'least-cost formulator' programs. With insufficient insight into the full composition of algae biomass, those new to the industry are often tempted to consider a very restricted set of value generating properties during the value determination. This limited input results in unbalanced and extreme price settings, both high and low. Indiscriminately focusing for instance on the concentration of crude proteins, carbohydrates or fats in the biomass will generate fairly low prices. Conversely, by equally indiscriminately focusing on high value products, such as astaxanthin or beta carotene, very high prices will be generated. Obviously the truth is somewhere in the middle. Establishing reliable valuation rules for bulk algal biomass is clearly one of the more important issues that need to be dealt with in the algae industry.

Fortunately, in establishing valuation rules the algae industry does not have to start from nothing. There are already a few sets of methods to determine the value of algal biomass, albeit predominantly for specialty markets. The present day annual turnover of micro-algae business is between $ 750 million and $1,000 million USD. One of the higher value products derived from micro-algae is astaxanthin, a carotenoid, which at pure concentration sells at $ 10.000 to 15.000 per liter. This is a high value cosmetic and pharmaceutical ingredient with a limited worldwide production capacity. Clearly, scarcity is an important driver of the value of this product. Focusing on the content of similar high value compounds would result in a very high price setting for the diatom meal. This high value would not only be prohibitive for larger volume markets but is actually improbable as scarcity would no longer be a driver. For establishing the rules an adaptation towards larger volumes is needed.

One of the larger markets for micro-algae is found in the aquaculture industry. Whole micro-algae are being used as essential food in the aquaculture business. These micro-algae sell at prices ranging from $70 to $360 /pound. Feed specialists pay premium prices for the exceptional nutritional qualities of micro-algae which are indispensable during the larval and juvenile life stages of fish, shrimp and other aqueous animals. Because of their vital role in the development during juvenile stages, micro-algae can be considered as 'baby-food for fish'. There is an extensive body of scientific knowledge about the nutritional benefits of micro-algae in aquaculture applications.

The largest volume of traded micro-algae today consists primarily of the cyanobacteria *Spirulina*. This alga is typically sold at $2.25-$6.80 /pound. At that price setting it is at the lower end of the value chain of the present day micro-algae business. The value of this alga lies mainly in its high protein content and the fact that it contains many essential amino acids. This alga is commonly used as human food supplement and also as animal feed, for instance for race horses. It is also the source for the extraction of the pigment phycocyanine which forms the basis of one of the few natural blue coloring agents that is used in food. Cultivating *Spirulina* is a booming business in countries such as China (Fishstat).

Essential fatty acids (EFA), such as the omega 3 fatty acids, are another set of molecules that add value to micro-algae. EFA's are indispensable for the development of the brain, eyes and cardiovascular system in fish and shrimp but also in mammals, including humans. Algal oil rich in omega 3 fatty acids sells at prices ranging from 50-60 $/liter.

Thus, the present day list prices for micro-algae range roughly from $2.25 to $225 /pound. The value is determined by a combination of quality and quantity: for instance protein content and presence of essential amino acids, fat content and fatty acid typology, carotenoids for colouring and for anti-oxidative properties, phytosterols for development and probiotic immune-stimulants.

Positioning diatom meal is essential for the economical model. Diatoms are exceptionally rich in omega 3's, sometimes up to 35% of the total fat content, and are rich in all essential amino acids (e.g. lysine). Furthermore, they are rich in phytosterols, exhibit immune stimulatory and developmental properties, they contain anti-oxidative molecules and they naturally exhibit antibiotic properties against multi-resistant diseases (e.g. MRSA). Clearly, both quantity and quality is present. The price setting of diatom meal will be the result of a balance between all these useful properties while being weighted by the fact that diatom meal will be abundantly available on the market place in due time.

## Concluding remarks

We live in challenging times. In about a decade we will need to feed another 2 billion people and we need to find a sustainable source of energy. A second green revolution is clearly required and land based agriculture is nearing its limitations. This second green revolution will therefore not be land based but will be drawn from the oceans. Micro-algae have been part of the human heritage for thousands of years and will become much more important in our food and fuel provisions. As a result of this revolution nutritious biomass will be produced by the cultivation of micro-algae at industrial scale.

Depending on the micro-algal species and ecological group there are various ways to produce micro-algae. One method that was developed in the past decade focuses on attached diatom algae and in its industrialized format is referred to as the DIAFORCE™ platform. Diatom farms based on this platform are fully operational at pre-industrial scale for some time now. It has been shown that these farms can produce 40 to 60 tons/acre/year and the resulting biomass can contain up to 20-30 % of triglyceride storage oil. The production technology is available and industrially scalable.

Even more importantly, there is an economic reality behind the industrial scaling. The basics of the business models for the algae industry have been unveiled. Applying these insights on the business case for DIAFORCE ™ farms shows that diatom oil for fuel can be produced and this at prices of $50 -$150 /bbl. The two drivers that make this possible are sufficient scaling and realizing the inherent value of the residual diatom meal. Diatom meal has substantial nutritional value for human and animal. In fact diatoms form the basis of the ocean food chains and webs. This tremendous nutritional value can be translated into real business in several markets, both human and animal. Diatom oil for bio-fuel purposes should be considered as a by-product.

Although feeding the people of the world is by itself a very admirable motivator, history has taught us that it will be the solid economic models that will ultimately be the key drivers of the second green revolution. The second green revolution will not be construed on an academic desk but will rise up from the international trade floors and algae-culturing farms. With diatom algae driving this next sustainable industry it appears that human and economical benefits may coincide.

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sustainable bio-engineering
for the aquatic environment

Koenraad Vanhoutte (1974)

Bio:

Dr. Koenraad Vanhoutte holds a PhD in Biological Sciences and is specialized in micro-algae and microbial ecosystems. He holds a Master in Applied Biostatistics and Research Methods and received an MBA degree at the Vlerick Business School. During his academical career (1997-2004) he was a researcher at the University of Ghent, he trained dozens of algae scientists and is the author of various scientific papers and book chapters.

Some five years ago he started working together with expert engineers on diatom-algae based mass production technologies. This resulted in the development of various patented platform technologies, amongst others the DIAFORCE ™ platform. He is a founder of the company SBAE Industries which provides turnkey solutions for diatom-algae production for various sectors, including the energy sector. Today, he holds the position of Science Director in the company and is Chairman of the Board. He is a frequent speaker on algal technology at industrial events.

sbae industries

sustainable bio-engineering
for the aquatic environment

**FAQ's on diatoms and SBAE Industries**

**What is Diaforce® technology?**

Diaforce**®** is a proprietary algal production platform of SBAE Industries. In principle it imitates a running water system (e.g. a mountain stream). This technology grows mixed algae communities or poly-cultures that attach themselves on substrata (e.g. rocks). The algae in this technology belong to the group Bacillariophyta or diatoms. By using poly-cultures, running water and attached algae this production platform reflects a radical paradigm shift in algae cultivation.

**What are diatoms?**

Diatoms or Bacillariophyta are one of the major groups of algae. They are mostly unicellular but can occur in colonies. They live in both freshwater and marine systems. They are characterized by a unique cell wall made of hydrated silica. As such it can be said that diatoms live in glass houses.

**Why use diatoms?**

Diatoms are energetically more efficient than the average alga. Diatoms have evolved the accessory pigments, such as fucoxanthin. These pigments enable them to capture extra energy in the range of 450 to 540 nm and peaking at 510-525 nm.

They use silica to build their cell walls. This is substantially different from many other algae who build their cell walls from organic carbons such as cellulose and hemicelluloses. Depositing silica in structural forms requires only about 6.5 % of the energy required to synthesize cell walls from cellulose.

The advantages of diatoms are as effective as they are simple: capture more sunlight energy and use this energy more efficiently to produce cells. As a result some diatoms divide up to three and sometimes four times per day.

**Why attached algae?**

Attached algae are often found in locations were phytoplankton or free floating algae are not present as a result of the water flow. Attached algae stick to substrata and can thus not be carried away by the water flow. These flows do create a rather stressful environment in which the attached algae colonies are continuously losing cells. Therefore to maintain their biomass and position on the substratum they by necessity have evolved to divide faster than their free floating counterparts.

Growing attached algae enables us to harvest the algae simply by removing the substrata from the water flow. This methodology means that the volumes of water that need to be processed are at least two orders of magnitude less than conventional systems. As a result of the selective use of attached algae, new ways of efficient and economical harvesting have now become available.

**Why poly-culture?**

A poly-culture is simply more productive than a mono-culture, because each different species can use some resources not used by the others. This is the way of nature. This is comparable to tropical forests that produce more total biomass than a cornfield, even on the equator. Moreover, poly-cultures are much more stable in productivity and are resistant to invasion of undesired species.

**What is the maximum amount of algae that can be produced theoretically?**

First, let us consider the source of biomass. The process of photosynthesis captures sunlight and converts this into biomass. Thus both the amount of sunlight available and the efficiency and speed of the photosynthesis process are determinant of the amount of biomass potentially produced on a given spot on the planet. For instance in the south of Spain one could calculate that the theoretical maximum is 110 tons /acre/year. But theoretical maxima are rarely attained.

However, this estimate is only considering autotrophy and photosynthesis. This line of thinking does not consider the fact that micro-algae have for millions of years been competing with each other for that same sunlight. Needless to say that they have developed (evolved) numerous methods to outcompete their competitors. Micro-algae have evolved accessory pigments, which enable them to capture sunlight more efficiently and even use different light spectra. They have also developed ways to be parsimonious with the use of their ‘organic carbon storage’. Some algae groups use other elements that are energetically more efficient such as the diatoms which use silica to build the cell wall instead of organic carbon. Undoubtedly there are numerous other tricks that are as yet unknown.

These competitive tricks of the trade show that production potential strongly depends on the group of algae under consideration and may range between 20 and 120 tons/acre/year.

**How much algae can 1 hectare of DIAFORCE™ produce?**

From field tests and pilot plants, operating during periods exceeding one year (including winter), it was determined that a DIAFORCE™ production facility can produce between 40-60 tons/acre/year of biomass in temperate climates.

**How does this compare to 1 hectare of conventional open pond systems?**

Conventional open pond systems in temperate regions can produce from 4 to 10 tons/acre/year.

**Why the big difference?**

Diaforce™ uses attached algae and more specifically diatoms which by their natural properties divide faster than the average algae. By growing more energy efficient algae, more biomass can be produced on the same surface unit of land.

**What is poly-modulation $^{TM}$?**

Poly-modulation $^{TM}$ is the set of concerted actions which result in the induction to produce storage lipids by micro-algae by synchronization of various intracellular processes. Poly-modulation is proprietary technology of SBAE Industries that increases the oil content in diatom biomass.

**How much CO2 is consumed by algae?**

This question may seem simple but it isn’t. From the Redfield ratio (C:N:P=106:16:1) it can be deduced that 100 ton of algae contain about 31 tons of carbon, this corresponds to about 114 ton

$CO_2$. This is assuming a protein content of 34% (on a dryweight base). However, depending on the storage molecules (oils, carbohydrates) built up in the algal biomass this could be substantially more.

A rule of thumb could be 1.5 tons of $CO_2$ sequestered for each ton of algal biomass.

**What is photosynthesis?**

Photosynthesis is the metabolic process by which solar energy is embedded into biomass. This process fixes solar energy with carbon dioxide and water into organic carbons and releases oxygen as by-product. Organic carbons are both energy storage for the cell and building blocks of biomass.

**What is primary production?**

Primary production is biomass that results from conversion of inorganic elements (e.g. $CO_2$) to organic molecules (e.g. oil). Most primary production occurs through the process of photosynthesis. One third of the global primary production is done by micro-algae and they produce about 50% of the world oxygen.

**What is silica?**

Silicon is the second most common element on earth. In its oxidized form it is known as silicon dioxide or silica. Silica is more commonly known as ‘sand’ (e.g. quartz, cristobalite, etc.).

**What is silica used for?**

Silicon is used in various sectors, such as construction materials, fine chemicals, micro-electronics and computer chip production, filtration and separation, medical applications and nanotechnology. The value of silica is determined by its physical properties and degree of purity.

**Is growing algae for biofuel economically viable?**

Today, the answer would have to be ‘no’, much the same as was the case for the first cars, the first computers or the first barrels of oil. The question one should ask is whether algal oil will become economically viable in the foreseeable future? Then the answer is definitely: ‘yes’. With oil prices being what they are and with an ever increasing energy demand there will be a moment during the next decade when petroleum will be more expensive than algal oil. Especially, once all the hidden costs of oil production are included, such as the volatility of energy prices, security of supply and the ecological footprint. ‘Economical viability’ can be measured in more ways than one, the real measure is ‘total cost of ownership’.

In addition one should consider that algal biomass contains much more than merely oil. It should be understood that in order for the algal biomass to have a maximum value, the various compounds should all be commercialized. For instance, algal biomass is exceptionally rich in proteins and holds par with fish meal when it comes to essential amino acids.

References can be obtained upon request.