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TURNING TRASH INTO CASH: MICROALGAE CULTIVATION TO MITIGATE ENVIRONMENTAL WASTE IMPACT

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EXECUTIVE SUMMARY

Global manufacturing industries are facing the double-edged sword of commercial and environmental pressures. Companies operating in fields as diverse as agriculture, aquaculture, brewing, food production, water processing or cement production, are wrestling with the problems inherent in producing large quantities of CO_2 and / or nutrient-rich wastewater. Disposing of such waste is expensive. It's also fraught with risks, not least the peril of adverse publicity that surrounds an environmental mishap or accidental release to watercourses.

There is, therefore, an increasing imperative to turn these waste streams into sources of revenue rather than cost.

Simply releasing waste streams into the environment is adding, incrementally and relentlessly, to the global environmental crisis. With the sustainability imperative looming large, 'net zero' ambitions will be translated into regulatory changes in every major economy. Dealing with wastewater or flue gases is going to be even more expensive in a net zero regulated world.

Our whitepaper considers the opportunities for using these nutrient-rich sources as the input for microalgae cultivation. This could be considered simply as a method of carbon capture, but is more likely to yield benefits in the creation of valuable bio-derived compounds. The process involves intercepting waste streams and diverting them into feedstocks for the generation of new revenue streams. This promises to replace the negative environmental impact with valuable new co-products in a transformative, circular-economy model.

This is possible because photosynthetic organisms, such as microalgae, can rapidly capture CO_2 and other environmentally damaging waste products and embody them into biomass. Ideally, there is no need to separate the harmful materials from other waste gases and liquids. Consequently, these organisms have the potential to both alleviate the harmful effects of waste streams and generate new high-value products. The possibilities are particularly potent for those in the food and beverage sector because the waste stream can be turned into highly valuable products for human consumption.

Many organisations have explored microalgae cultivation, with varying levels of success, from the 1970s onwards. Some have disregarded or discarded the opportunities in a field known for its complexity and cost. However, recent technological advances make the field radically more attractive than at any time in the past.

Previously, the economic viability of algal cultivation was limited by a range of problems, from low biomass or biomolecule yields to further diminished yields under varying growth conditions and high energy costs of harvesting. Innovation has now provided the tools to both improve yields and reduce costs. High-efficiency, low-cost lighting has made a radical difference to the economics of production. Improved harvesting methodologies together with great strides in automation, sensing and closed-loop control have reduced the variability and uncertainty inherent in any biological system. Lately, the ability to perform gene editing of algal strains has enabled a far greater suite of compounds to be produced. These new cultivation and harvesting techniques have proven their feasibility in lab and field trials.

This paper shows how microalgae can be both sustainable and revenue-generating when implemented correctly. We strongly advocate a bespoke approach to ensure that cultivation systems are optimised for the co-production of new compounds or 'products.'

The quantities, composition and impact of waste streams vary widely between businesses and sites, over time, and between industries, so the optimal approach will also vary significantly. In the interests of space and clarity we only discuss autotrophic organisms using light in this whitepaper, not hydrotropic, but the reader will readily understand that many further possibilities can be imagined. Any approach must embrace a range of disciplines, techniques, and insights – an introduction to which is presented here.

1 INTRODUCTION: A NOVEL SOLUTION FOR MITIGATING ENVIRONMENTAL WASTE

1.1 THE PROBLEM

Almost all industries that use fossil fuels generate large quantities of CO_2 and many businesses – including agriculture, aquaculture, brewing, water processing and oil and gas extraction – produce nutrient-rich, environmentally harmful wastewater. The emission of these waste materials into the environment is a major cause of the ongoing climate emergency. Growing awareness of the impact of these processes is driving an increase in net zero targets, corporate social responsibility and other incentives that are placing pressure on businesses and governments to decrease the impact of their waste streams.

Many strategies have been proposed to reduce the effect of anthropogenic CO_2 emissions on the global climate. They include reducing use of hydrocarbon fuels; direct air carbon capture and storage (DACCS) that captures CO_2 from the air in minerals, agricultural land, biomass, or other products; and carbon-capture, utilisation and storage (CCUS) techniques that concentrate CO_2 from exhaust flues and capture it in products or geological features. CCUS can be effective to minimise CO_2 emissions from a point source emitter, but many of these techniques have high parasitic energy costs and huge infrastructure requirements and are unsuitable for single businesses or sites.

The discharge of nutrient-rich wastewaters into watercourses is common.[1] It can lead to uncontrolled wild algal blooms and eutrophication events in water courses, coastal areas downstream and even oceans.[2 3 4] This has serious environmental consequences including production of toxins dangerous to fish and other animals (including humans); blocking of light to other photosynthetic organisms; oxygen depletion and 'dead zones'; fouling of equipment and hardware in the watercourse; and increasing treatment costs for drinking water.[5 6]

For many businesses, reducing CO_2 emissions and treating their emitted wastewater to remove nutrients and minimise uncontrolled discharge will significantly reduce their environmental impact. But the cost of performing this waste minimisation is naturally a blocker to many industries adopting them in the absence of robust government incentives or regulatory pressures. In keeping with the circular economy model, it is desirable to be able to extract value from these waste streams, either to make money or to simply offset the cost of the treatment.

1.2 ALGAE COULD BE THE SOLUTION

Photosynthetic organisms naturally take CO_2 and other nutrients and convert them into biomass. Algae represent a particularly effective group of organisms for this role due to their very high growth rates, and have been proposed for CCUS schemes for over 20 years.[7] Furthermore, it is these organisms that undergo rapid growth in nutrient-rich water and that are responsible for the environmental damage caused during eutrophication. One viable strategy to mitigate the damage caused by CO_2 and/or aqueous waste streams is to take photosynthetic organisms and cultivate them in a controlled manner so that they deplete the environmentally damaging chemicals from the waste streams before they are emitted into the environment. This strategy is particularly valuable when these waste streams are co-located and both CO_2 and nutrient-rich wastewater can be successfully exploited.

The term algae refers to a very diverse, and poorly defined, group of organisms that includes both microalgae and macroalgae. Microalgae typically refers to both microscopic and single-celled algae (including diatoms) and oxygenic photosynthetic bacteria. Macroalgae refers to macroscopic, multicellular organisms often known colloquially as seaweeds. While the latter are often valuable, they are not the primary focus of this report.[8] All algae share the common features of being non-vascular, photosynthetic organisms that rely on aquatic or semi-aquatic conditions. They often produce numerous useful biomolecules and exhibit high growth rates compared to terrestrial plants (see Section 3.3) and it is this that makes them organisms of extreme interest. Algae cultivation offers an unusual opportunity to engage in sustainable treatment of wastewater or carbon capture, while creating new high value products.

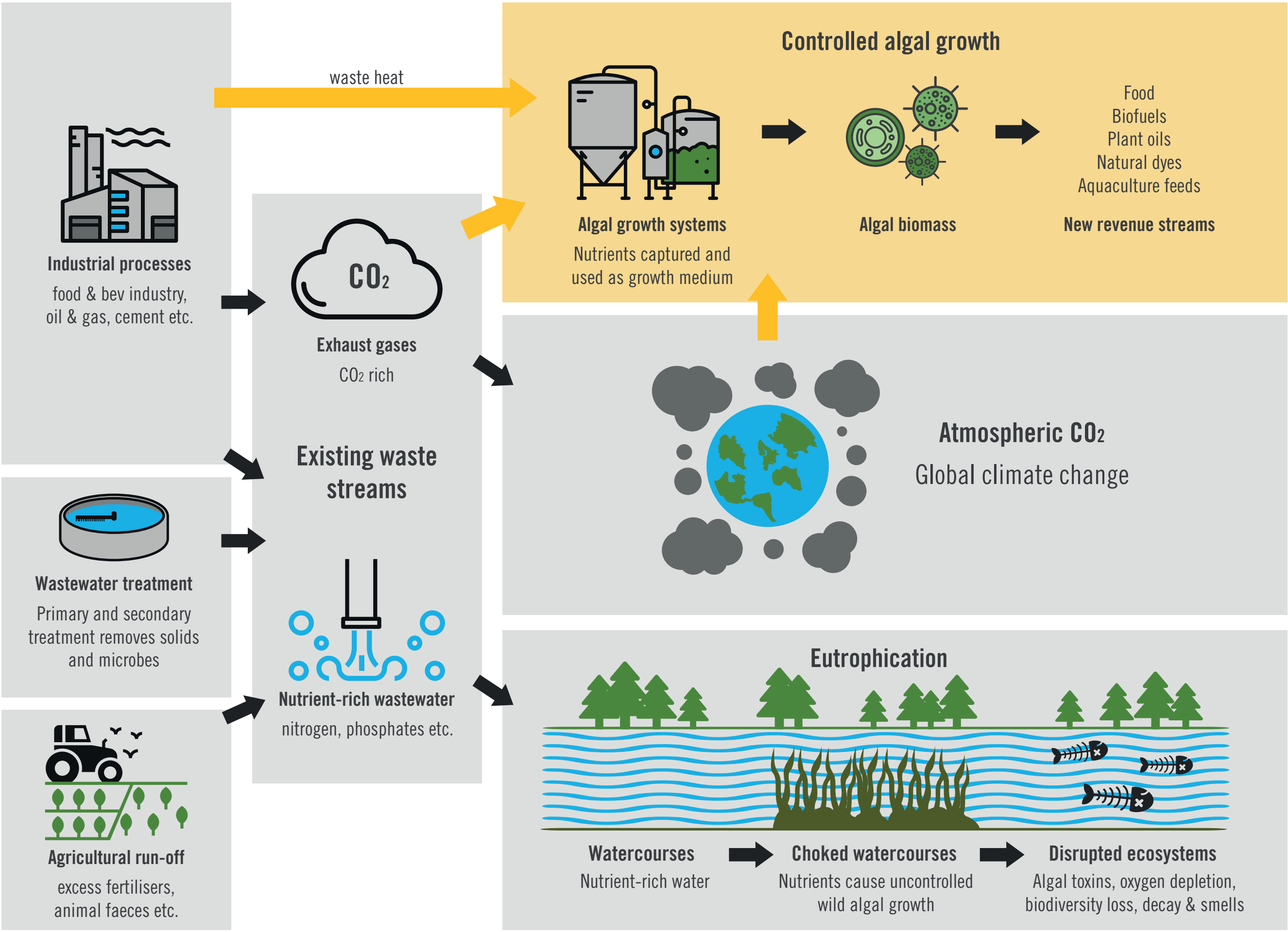

FIGURE 1: Exhaust gases and nutrient rich water waste-streams can be intercepted and exploited to generate numerous products and revenue streams.

2 WHAT CAN ALGAE DO?

2.1 SEQUESTRATION OF CARBON DIOXIDE

While there are many physiochemical techniques available for CCUS, the use of photosynthetic algae for both carbon capture and wastewater treatment has several advantages. Firstly, since algae can tolerate high concentrations of CO_2 and other waste gasses, they do not typically require CO_2 to be purified from other exhaust gases or compressed. This significantly reduces the parasitic energy requirements compared to many other carbon capture techniques, making it particularly suitable for small and medium sized emitters.[9] Secondly, the algae embody the carbon into biomass without the need for 'carbon utilisation' processes such as mineralisation or chemical reactions to form commodity chemicals. Thirdly, there is a wide range of commercially viable products that can be produced from algal biomass and sold to offset the cost of cultivation.

Algae also represent a more compelling group of organisms for this application than terrestrial plants due to their higher photosynthetic efficiency. Algae have been reported to have a photoconversion efficiency (PCE, a measure of incident energy relative to extracted energy) of 6.3%, which is significantly higher than even the most productive terrestrial crops, such as elephant grass (*Miscanthus spp.*), that achieve 1-2%.[10] This gives algae a high growth rate and allows them to sequester carbon faster than terrestrial plants and makes them a viable organism for use in biological carbon capture.

Under non-starved, fully autotrophic conditions, 1 g of algal biomass production is formed as a result of the capture of 1.76 g of CO_2. Some strains can also remove NO_x species from flue gases, however, heavy metals and SO_2 can produce adverse effects. The photosynthetic fixation of atmospheric CO_2 to biomass is a quantised process and is directly limited by photon flux and cell shading. Therefore, both the algal yield and the amount of CO_2 fixed is proportional to area that is shaded by the algal culture, local insolation and culture density. Best case realistic scenarios in areas of high insolation corresponds to 10-80 g m^{-2} day^{-1} of biomass production (depending on cultivation method, see Section 4.2), which sequesters up to 140 g m^{-2} day^{-1} of CO_2.[10]

> *"Algae cultivation offers an unusual opportunity to engage in sustainable treatment of wastewater or carbon capture, while creating new high value products"*

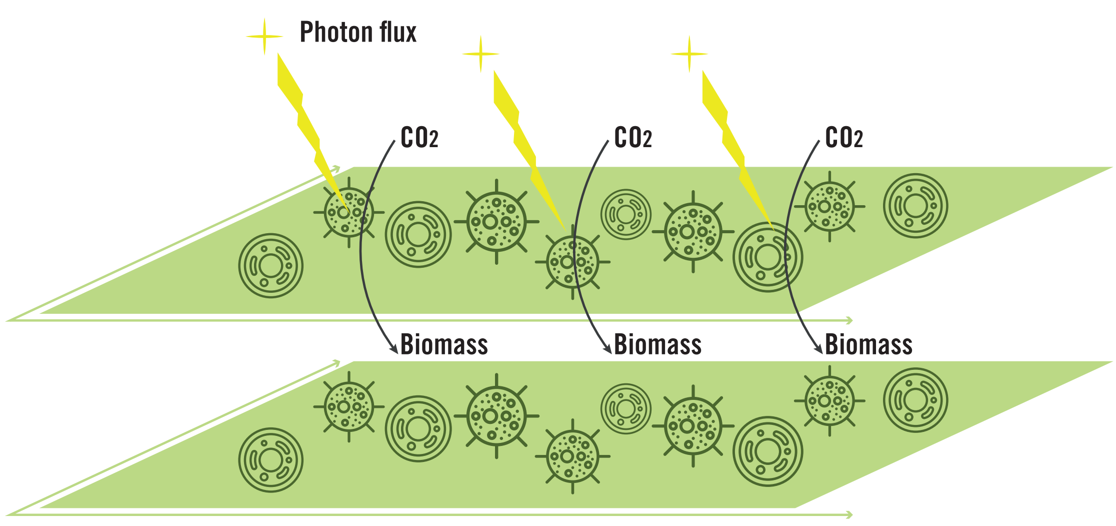

FIGURE 2: Carbon capture by photosynthetic organisms is determined by both the photon flux and also the density of cells

2.2 TREATMENT OF WASTEWATER

Despite the ease with which microalgae can grow in unpromising circumstances they are still plants, and still need large quantities of other micronutrients such as nitrogen, potassium, phosphorous, iron, magnesium etc. These nutrients can be manufactured and purchased specially for the purpose, or they can be utilised from waste (which people are getting rid of) i.e. either a cost or a way of offsetting others' cost.

Aside from carbon capture, algae also present a compelling proposition for treating nutrient-rich waste streams, such as those from agriculture and food or beverage production. Nutrient enrichment of water is increasingly becoming problematic worldwide, leading to eutrophication and oxygen depletion in inland waterways and coastal areas.[2,3,4] From a commercial point of view, these nutrient-rich waters can be used to replace or supplement the use of fertilisers, water or growth medium for algae cultivation. If the desired end product is for a food-safe application, then nutrient-rich, food-safe wastewaters (for example from agricultural products, distilleries and the food industry) can be very valuable.[11] Examples of suitable sources of waste waters that have been demonstrated to be suitable for algae cultivation include the food industry (for example, cheese production, vegetable processing, sugar production);[12,13,14]beverage industry (such as breweries and distilleries); [15,16,17]drinking water industry (nitrate rich brines from the ion-exchange columns used to produce drinking water for example);[18] aquaculture;[19,20,21,22,23] oil and gas industry by-products (produced water);[24] and domestic wastewaters.[25,26,27,28,29] These application areas are thought to be particularly applicable to heterotrophic fermentation, where algae are grown in the dark on sugars, which are converted to oil and biomass.

There are significant variations in nutrient concentration both between and within these industries. Even after a particular wastewater stream has been selected for algal cultivation, the raw wastewater may still require some degree of treatment as they typically contain high chemical oxygen demand (COD), biological oxygen demand (BOD), dissolved and suspended solids (TDS/TSS), and the presence of other microorganisms that could be inhibitive to culture growth. Thus, it is essential for each company to characterise its own wastewater stream, to determine the control design to optimise wastewater treatment, carbon sequestration and/or production of a specific algal strain.

In addition to treating nutrient-rich wastewater, there are also examples of microalgae being used for other forms of environmental remediation. Algae can be used to remediate heavy metal polluted water by adsorbing the metal ions, binding them onto the cell surface and to intracellular ligands.[30] Similarly there are examples of using halophilic microalgae (e.g. *Dunaliella salina*) to valorise or treat toxic hypersaline brines.[31]

2.3 GENERATING HIGH-VALUE PRODUCTS

Since algae can be cultivated using waste CO_2 and water, the products arising from their cultivation can be made in a highly sustainable fashion. Being able to exploit these health and sustainability credentials may be a way to drive engagement and sales with valuable sectors of the consumer market.

The most significant recent trend in new food products in the developed world is often termed 'clean label', a blanket term that includes 'organic', 'natural' and 'free-from' products. This trend is largely driven by increasing customer awareness of health and sustainability issues. Growth in the clean label is in strong contrast with the relative stagnation in the food and beverage industry in general.[32] This is why large consumer corporations such as Unilever have been investing heavily in vegan and alternative protein sources.[33] More generally, demand is set to increase for protein for both human and animal consumption. Single-cell proteins, including microalgae, are expected to form a significant part of this mix.[34]

Algae biomass consists of three main (macronutrient) components: carbohydrates, proteins and natural oils (lipids) and many strains also produce useful micronutrient fractions. Depending on requirements, producers can make use of the 'whole algae' in its entirety (for example, selling as wholefoods for humans or agriculture and aquaculture) or they can fractionate the desired component to give purified and higher-value products (see Figure 3).

For many years the algae market focused on maximising the high-volume, low-value lipid-fraction of algal biomass, especially the up to 60%wt of biomass lipid fractions for use as biofuels. However, algal biofuels have struggled to gain a commercial foothold and it has been found that 'high-value' products, such as food supplements, cosmetic base ingredients, and pigments are more commercially viable. Given the range of constituent substances that make up the

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IMAGE 1: Spirulina based products

whole algae, many sources suggest using a biorefinery model to ensure financial viability. In such a model, both the low-volume/high-value products (micronutrients, pigments) and the high-volume/lower-value products (fertiliser, aquaculture feed, fatty acids, biofuels) are extracted and purified from the algae biomass.[35]

A large variety of microalgae, diatoms and cyanobacteria have been exploited for commercial purposes. Examples of the wide range of products that can be produced from algae include:

- **WHOLE ALGAE** for human consumption or incorporated into nutraceuticals and cosmetics. *Arthrospira platensis and Chlorella spp.* (colloquially known as spirulina and chlorella respectively) are the most commonly cultivated microalgae and are rich in high quality proteins, Omega-3 & -7 oils, carotenoids, and essential minerals. As of 2018, the value of consumable algae supplement market was $800M, with a Compound Annual Growth Rate (CAGR) of 5%, a rate of expansion expected to continue through at least 2027[36]
- **OMEGA OILS** for food supplements. The polyunsaturated fatty acids (PUFAs), including Omega-3 and -7 oils, are of particular interest since they are essential to human nutrition and algae are an abundant and vegan source
- **PLANT OILS** for cooking or industrial purposes. Plant oils, such as palmitic acid are vital feedstocks in industrial process to produce foods, cosmetics and other household products. Approximately 200 million tonnes of plant oils were consumed worldwide in 2019/20,[37] and existing cultivation methods, using less efficient terrestrial crops, have had catastrophic environmental effects due to deforestation and land-use change
- **BIOMOLECULES** such as pigments, vitamins, sterols, phytohormones, polyphenols.[38] Of particular interest are the numerous commercially valuable natural pigments contained by photosynthetic algae species. These include carotenoids such as *ß*-carotene and astaxanthin from microalgae such as *Dunaliella salina* and *Haematococcus pluvialis* respectively, or phycobiliproteins such as phycocyanin (spirulina blue) – the only naturally derived blue food colouring that is both generally recognised as safe (GRAS) and stable at room temperature
- **AQUACULTURE AND AGRICULTURE FEEDS.** Algae meal can be used to supplement, or partially or wholly replace fishmeal or soy protein, (which often have significant environmental impact) in aquaculture or terrestrial agriculture, commonly with an improvement in growth and immune responses.[39] Aquaculture is an enormous and rapidly growing market globally with a compound annual growth rate of around 5.3% and expected to reach a value of $242 billion in 2022 [40]
- **BIOFUELS.** The relatively high cost and small-scale of production means that these have never been commercially competitive, relative to the very low cost of conventional fossil fuels, and are unlikely to be for the foreseeable future [41] [42]

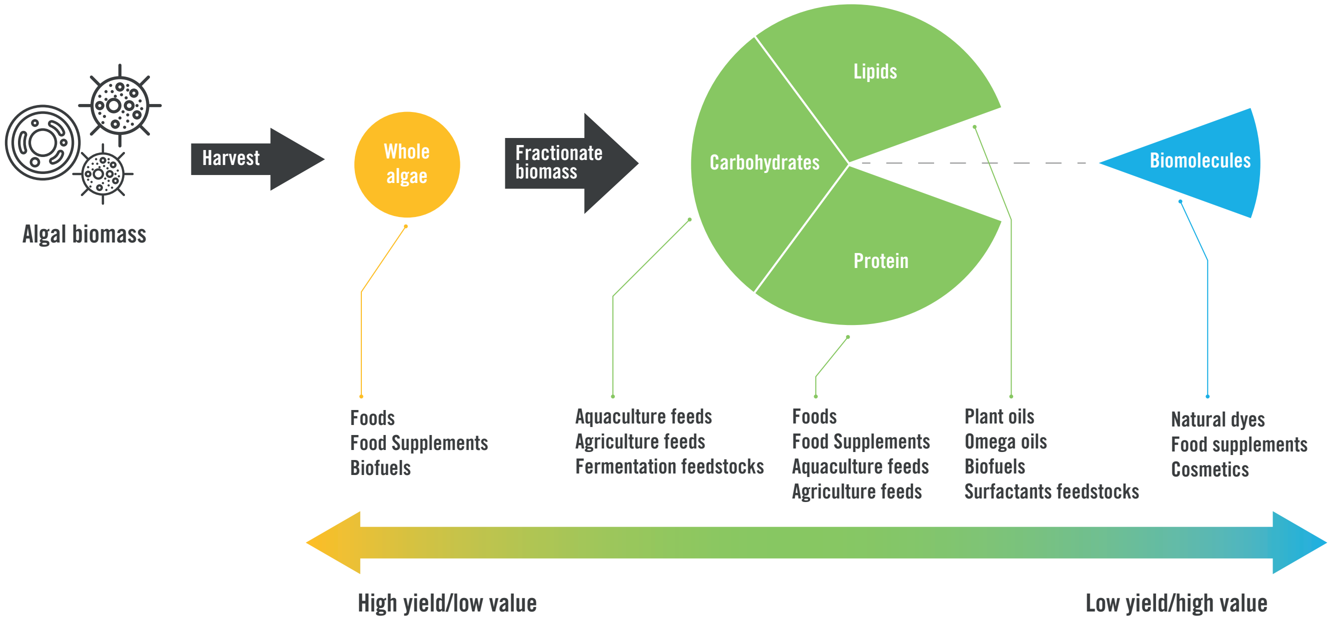

FIGURE 3: Whole algae biomass can either be sold as a bulk product, or processed to produce a number of products from the various different biomass fractions.

In summary, algae are extremely versatile organisms, which are capable of producing a very large range of products from a correspondingly large range of feedstocks, including common waste streams. Many of the most valuable products are foods, meaning that the most valuable waste streams are food-safe. Interested organisations should aim to design a system based on their priorities, which may include:

- Maximising biomass production (and hence carbon capture)
- Consuming more of a given nutrient from a waste stream
- Valorising a given waste stream
- Producing more of a preferred product
- Robustness to fluctuating conditions and feedstocks such as temperature, pH, salinity, nutrient availability, and culture competition

It is clear then that a holistic view of the system is required to maximise economic and sustainability value from a system. This includes understanding: the target production model including values and quantities; the available waste streams and how to maximise their use; the costs of any supplemental water or nutrients; the land area available; and the typical weather conditions. These factors will all define the system design, the options for which are covered above.

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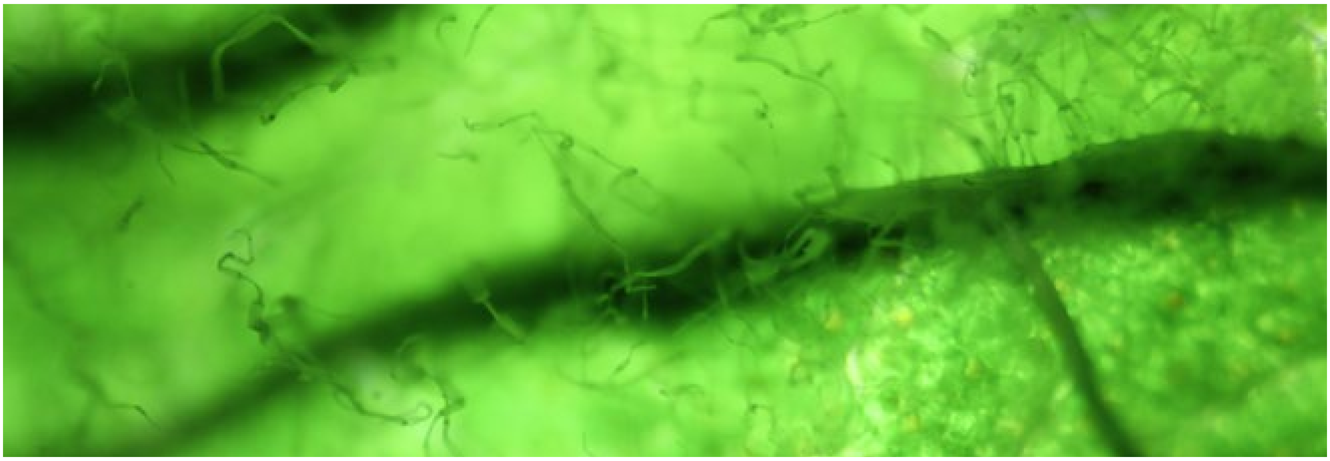

3 WHICH ALGAE DO I USE, AND HOW DO I GROW IT?

3.1 ALGAE STRAIN SELECTION

A critical step in the design of an algal growth system is the selection of the algal strain. This selection is informed by both the desired end product and the available feedstocks or inputs. There are a truly enormous number of algal species that can be cultivated, allowing the producer to select or selectively breed strains that best suit their cultivation conditions. Some strains will naturally produce more quantities of preferred products than others, while certain strains will be hardier to changing conditions such as temperature, pH, salinity and culture competition.

Examples of commonly cultivated species of microalgae include: *C. vulgaris* and *A. platensis*, grown as food and food supplements; *Scenedesmus spp.* and *Nannochloropsis spp.* that are attractive due to their high plant oil content; and a wide variety of species, for example *H. pluvialis*, that are commonly cultivated for micronutrient fractions such as carotenoid astaxanthin. Extremophile organisms can be cultivated in environments unsuitable for other organisms. For example *D. salina* grow in highly saline brine and is used to generate carotenoids that have applications in cosmetics and dietary supplements – this allows valorisation of an otherwise almost worthless and environmentally damaging waste stream.

3.2 ALGAE CULTIVATION SYSTEMS

Various concepts for algae cultivation can be considered, each of which have distinct advantages and disadvantages. They can vary in importance depending on the desired algal strains and end products (see Figure 4). These range from entirely 'natural' systems (such wild harvesting) which take on primarily uncontrolled inputs, to systems with control over all input parameters including feedstock, LED lighting (with control over desired wavelength emission), CO_2 and water/nutrients. In this case the inputs can be adjusted to optimal set points so that cultivation yields can be relatively predictable and high. However, such a system necessarily has a high operational cost and may not be able to adequately exploit waste streams which may vary in composition over time. Therefore, a partially input-controlled system that uses a dynamic control system to maximise yields from inconsistent inputs may be valuable for striking a balance between high yields, minimising costs of inputs, and the sustainability of the operation. Such a system has been enabled by modern sensing and control systems (see Section 4.4).

While microalgae can be more photosynthetically efficient than terrestrial plants, carbon sequestration by photosynthesis (in the absence of artificial lighting) is fundamentally linked to the area of land shaded – leading to very large cultivation systems. A major factor here is light transmission, governed by the Beer Lambert law – penetration within a dense culture means a requirement for high surface area.

This is significant in that in many parts of the world there is already significant strain on native habitats due to encroachment of agricultural land. So when designing an algal growth system, it is important to consider the land use being displaced by the cultivation site and for any developments to not exacerbate any existing pressure on land use. There are many examples of growth systems that have been developed to avoid these problems by being built into the fabric of the urban environment;[43] being built in unproductive land such as deserts;[44] or even floating in water bodies.[45]

Overview of existing algal growth systems:

- **OPEN PONDS** – these are large, shallow ponds that are often circulated with a paddlewheel. Ponds are the most prevalent cultivation system, and thanks to their low capital expenditure (CapEx) can be built on large scales (typical yields of <25g m^{-2} day^{-1}).[44] However their open nature means that: they are easily contaminated; have a risk of culture organisms escaping (which may make them incompatible with gene-edited organisms); have high temperature variations which can affect growth rate; see high evaporation and high rates of gas loss from the large surface which means that high fixation of CO_2 is possible but not guaranteed

- **PHOTOBIOREACTORS** – these are closed systems, that have high productivity (10-70 g m^{-2} day^{-1}) and allow control over all inputs such that conditions can be optimised for desired algal strain. They have a low risk of contamination, are highly modular, and are frequently employed commercially for capacities of 10,000 to 1,000,000 L of aqueous biomass. However, these systems have a very high CapEx and therefore are often limited in maximum size[46]

- **ATTACHED GROWTH SYSTEMS** – these are systems that are well established for the removal of dissolved nutrients in wastewater treatment, have a high productivity (30-80 g m^{-2} day^{-1}) and relatively low water requirements, but they require frequent harvesting and readily self-shade – which can significantly diminish productivity. There are two sub-types: algal turf scrubbers (for macroalgae),[47] and biofilm systems (for microalgae)

- **FERMENTATION TANKS** – these are large, closed fermentation vessels with an artificial light source and agitation to ensure that algae have exposure to light, similar to a conventional bioreactor. They are modular and can give a high volume of biomass for given footprint, however the requirement for artificial lighting means that they typically have a high energy intensity

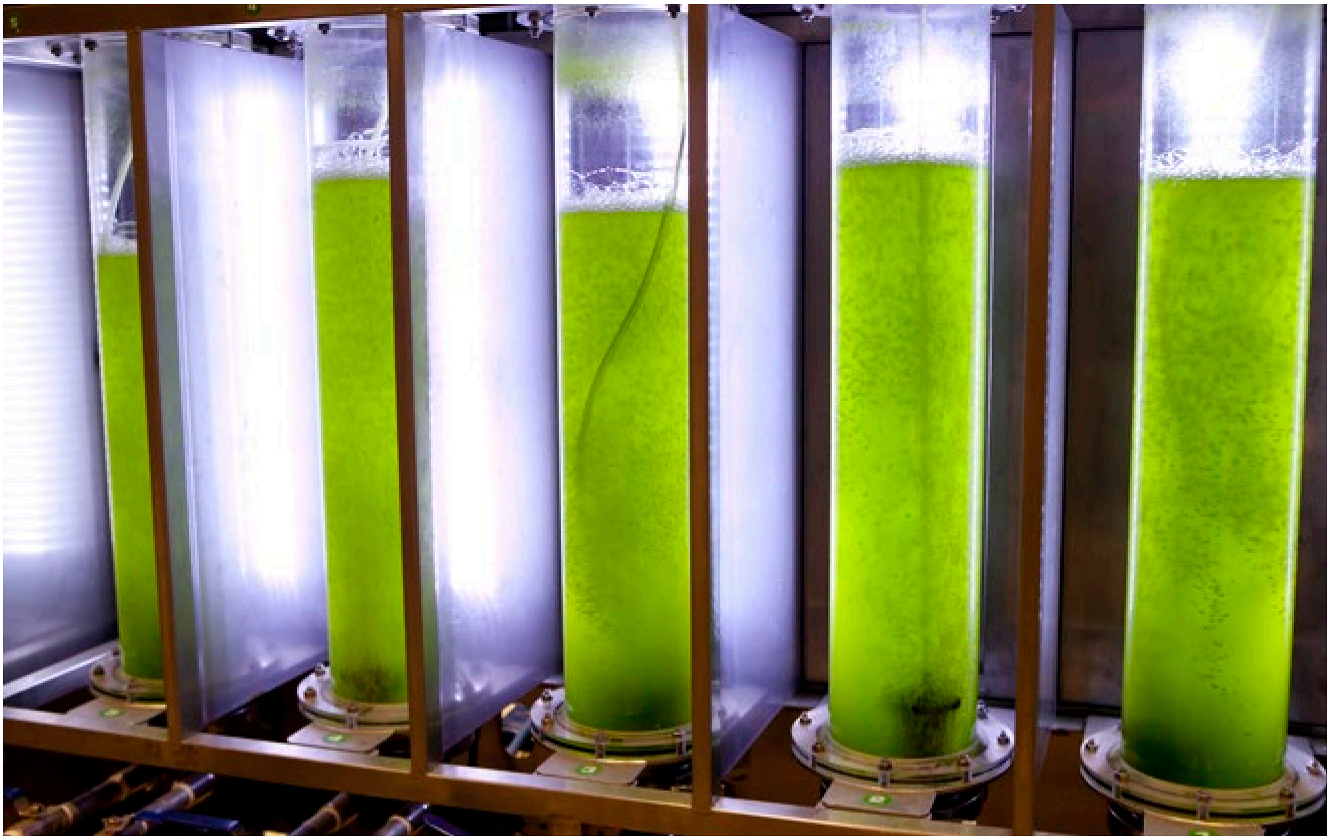

IMAGE 2: A photobioreactor - a bioreactor that utilizes a light source to cultivate phototrophic microorganisms

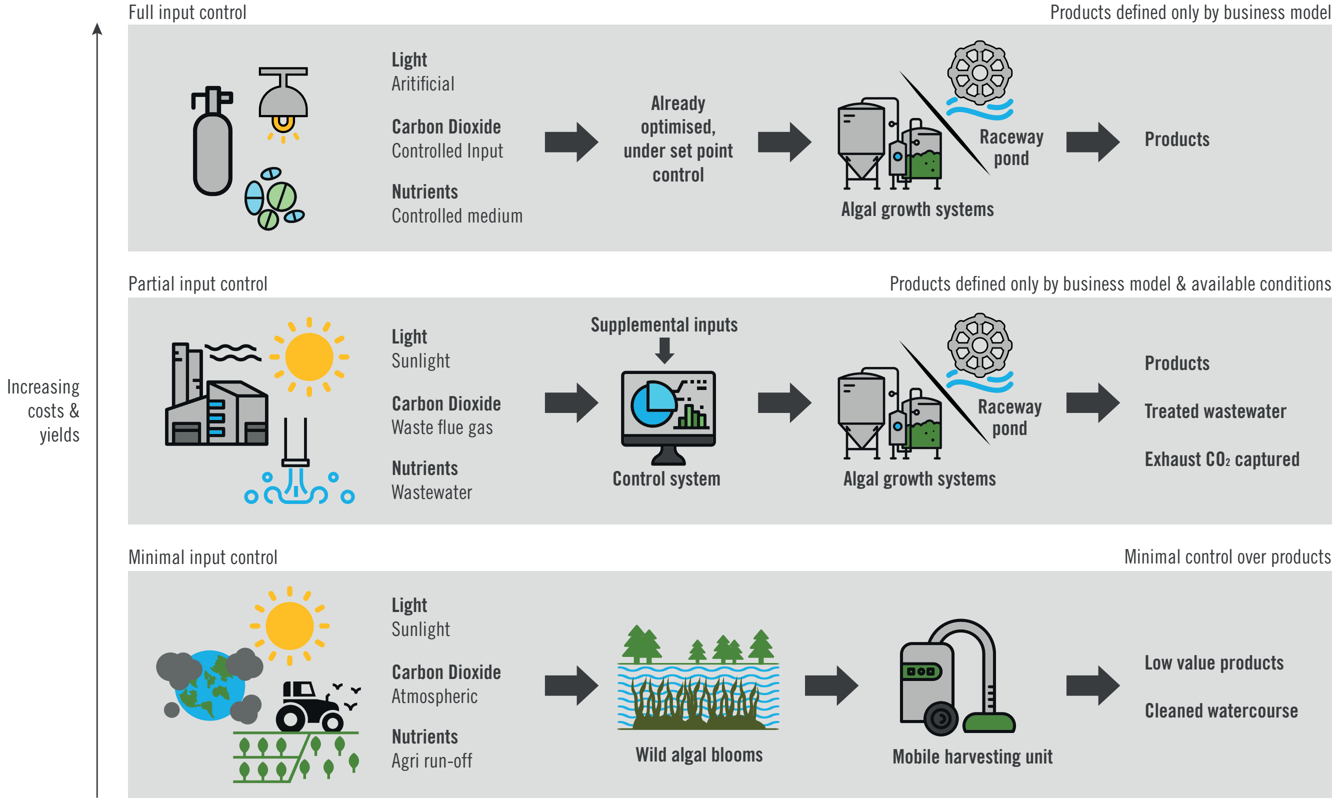

FIGURE 4: There are a wide range of different cultivation systems that can be used to exploit algae, ranging from: systems with complete input control, that can produce defined products in high yields but have minimal sustainability credentials; to systems with minimal control inputs and low yields but that can remediate environmental damage due to wild blooms.

3.3 HARVESTING AND PROCESSING

Algae is typically grown in a low concentration aqueous suspension, hence there is a requirement to thicken and dewater the algae into a slurry, or cake. In many cases, the algae must then be dried to preserve shelf life, either by drum or spray drying. For products that use whole cells, the processing can stop after the drying stage. Whereas for products that are not whole cells, there is a further requirement to disrupt the cells and fractionate the biomass (for example by milling, solvent extractions and so on).

The methods chosen for harvesting and processing vary depending on the end product, as there are a multitude of factors to balance including cost, chemical contamination, scalability, time, cell preservation and drying capabilities. This variation means post-cultivation processing can contribute anywhere between 5-30% of total production costs and greenhouse gas (GHG) emissions, depending on the methods used. Therefore, methods must be carefully tailored and examined based on algal strain, target product and scale of operation.

4 TECHNOLOGICAL ADVANCES HAVE ENABLED NEW CULTIVATION PARADIGMS

4.1 HISTORICAL LIMITATIONS AND CHALLENGES TO ECONOMIC FEASIBILITY

All the systems described above are both technically feasible and demonstrated in practice. Unfortunately, despite the many positives of algal cultivation, its economic viability has been limited by several key problems including low biomass densities per volume of growth medium due to self-shading; low biomolecule yields under high growth conditions; the financial and energy costs of harvesting; diminished yields in fluctuation conditions; and that it has not been possible to use artificially lighting while also being carbon negative. It is these fundamental limitations to microalgae growth that have stimulated much of the research and development around these organisms and in recent years several general strategies have been created to address them.

4.2 TECHNOLOGICAL APPROACHES TO IMPROVE YIELDS AND HARVESTING

The vertical farming industry is currently booming and faces many of the same challenges as algal cultivation including lighting, water and feedstock management, and growth-stage control. Collaboration between the two industries is accelerating the progress of each.

Artificial lighting allows production to be disconnected from prevailing weather conditions and natural day cycles. It can also be guided much deeper into a cultivation medium than natural lighting (which is generally limited to illuminating the surface) resulting in a smaller footprint for a given production volume. Artificial lighting has seen four pivotal changes in the last few decades:

- Low-carbon electricity is cheaper than ever. For example, the price of electricity from photovoltaic systems plummeted by over 80% between 2009 and 2019, reaching as low as $0.01-0.02 per kWh in areas of high insolation.[48] This has opened the door to minimising or eliminating the environmental cost of artificial lighting in some locations

- Demand side management for mixed source grids can be employed so that electricity is used during periods of low demand. This strategy has been used in vertical farming and enables cheaper electricity and smooths the power output of a grid with high renewables inputs

- LEDs have become far cheaper, more efficient and more widely available, greatly diminishing electricity demand for lighting. They are also available in many wavelengths to tune the illumination spectrum

- Additional strategies have been developed to minimise lighting requirements, optimise growth and/or optimise specific develop stages of algae. Strategies include using a spectrum designed to match photosynthetically active radiation and flickering lights to minimise lighting costs while maximising growth rate

Until now, the major production and energy cost of algae dewatering during harvesting has been limiting for high-volume, low-cost products. However, recent technological advances have the potential to dramatically reduce these costs and energy requirements, allowing underlying business cases to be more scalable and economically viable.[49] Studies have also indicated that use of waste heat from co-located industrial processes can reduce the energy requirements for the drying/dewatering process.[50] [51]

4.3 GENETIC MODIFICATION

Innovations in the field of genetic modification have allowed novel methods to partially address the challenges and improve the economics of algal cultivation. Genetic engineering refers to the modification of an organism's physical characteristics by direct, artificial manipulation of its genome. This can lead to:

- Better performance, for example maximised production of biomass and/or other specific metabolites
- Completely new features, such as the production of proteins or metabolites which are not naturally produced by the unmodified organism

Recent years have seen an increase in genome sequencing techniques, strain development tools and genome editing technologies, which have significantly enhanced the genetic engineering of microalgal species.[52 53 54] In the last decade, advances such as discovery of new species and genomes,[55] novel omics studies and models,[56 57] and tools such as CRISPR/Cas9,[58 59 60 61] have all contributed to the blooming of examples of genetically engineered microalgae with improved performances and/or altered traits.

In attempts to improve biomass yield and CO_2 sequestration through photosynthetic efficiency, modifications of the enzyme RuBisCo and re-engineering of the Calvin Cycle, central to photosynthetic metabolism and carbon fixation, led to significant improvements in a number of strains.[62 63] Similarly, reduction in the activity of light-harvesting complexes by mutagenesis led to ~50% growth improvement of *C. vulgaris* when the strain was grown in high intensity light conditions.[64] This could help overcome shading problems which are common in high-density algal cultures.

Examples of gene editing to improve yields of valuable biomolecules include enhanced production of carotenoids in green algae and diatoms;[65 66] production of the valuable carotenoid pigment astaxanthin, usually done in *H. pluvialis*, was engineered in *D. salina* to simplify production conditions;[67] improved lipid accumulation, for example by insertion of genes from fungi and yeasts into *C. vulgaris,*[68] or by enhancements in total lipid content in cultures of *Nannochloropsis gaditana*.[69]

While gene editing may not be acceptable to all businesses or customer bases or geographies (e.g. EU vs USA), it is a tool that may prove to be extremely valuable to some when considered carefully and used responsibly.

4.4 IMPROVED SENSING AND CONTROL SYSTEMS

Many co-dependent variables must be kept in balance to maintain consistent healthy algal cultures and indicate problems. Factors such as CO_2 levels, illumination, pH and cell maturity must be monitored, and this becomes an increasingly complex challenge in the case of inputs outside of the user's control (e.g. sunlight levels or wastewater composition).

Improved control systems can be used to keep growth rates up, minimise CO_2 losses and minimise costs. Indeed, experiments have shown that Model-based Predictive Control (MPC) can make significant improvements in all three of these.[70 71] They can also improve disturbance rejection, which is particularly important in systems that can be affected by external inputs.[72] For example, using sunlight may be preferrable to artificial lighting but this introduces a highly variable input, which is not under the user's control. There have been experiments showing significant productivity gains from incorporating weather forecast data with a predictive model allowing control inputs to be changed in anticipation of the likely weather shift and sustain the overall productivity.[73]

Several techniques that enable closed loop control have become significantly cheaper in recent years. Sensing and monitoring (spectroscopy and multispectral imaging, for example) of cultures is essential for early indications of problems, such as contamination or impending colony collapse, which might require corrective action. This monitoring can now be conducted in-line, which gives continuous information about the process state, without the need to manually take a sample, prepare the sample and test it in the lab. This can also provide more robust data for process optimisation. Modern machine learning (ML) and analytics can be deployed to help us make the best use of all this data. For example, ML can achieve better than human performance at counting and classifying single-cellular organisms under a microscope, with applications ranging from optimizing lipid yields to early detection of bacterial or fungal contamination.[74]

Biological processes are complex, but with increasing amounts of sensor and monitoring data and robust control systems it will be possible to achieve high productivity with high uptime and drive down operational costs, even in the case of highly variable uncontrolled inputs.

5 CONCLUSION

Algae cultivation presents an opportunity for businesses to take significant action to both mitigate environmental impact and to create new value opportunities from existing waste streams. All the cultivation and harvesting techniques presented in this report have been demonstrated in lab and field trials to be technologically feasible. Implemented correctly, with a solution tailored to the specific requirements of a site, they also have the potential to mitigate the effects of harmful waste streams.

It is only relatively recently that the technological developments have enabled the possibility of an economically viable system that is also environmentally benign. There is therefore an opportunity for companies to gain a first-mover advantage in several fields.

For those interested in leveraging this approach, it is vital to first look at the specific characteristics of the waste streams to understand the opportunity. The key questions to be asked, beginning with the initial goals, are shown here:

LATEST TECH DEVELOPMENTS

1. **Ultra-low cost LEDs**
2. **Cheaper, more sustainable electricity:**
   a. Low carbon sources
   b. Demand-side managed mixed source grids
3. **Low cost and energy harvesting methods**
4. **Gene editing**
5. **Improved sensing and control**
6. **Developments in automation**

MY GOALS

1. **What are my reduction targets?**
2. **What waste stream(s) do I wish to target?**
3. **What opportunities should I prioritise?**
   a. Sequestering carbon
   b. Removing a specific nutrient
   c. Valorising a given waste stream
   d. Producing a particular product(s)

PERSONALISED SCOPING

1. **What are the concentrations/volumes of valuables and impurities within the target waste stream(s)?**
2. **What type of products should be targeted?**
   – high volume, low value (e.g. biofuels and aquafeed)
   – low volume, high value (e.g. pigments)
   – a mixture, suitable for a biorefinery approach
3. **What algal strains are suitable to produce the desired products?**
4. **What supplemental feedstocks are required to optimise biomass growth?**
5. **Are their any constraints on the system?**
   – location, lighting, temperature, available land area, target BoM cost…
6. **What are algae cultivation systems are suitable?**
   – open ponds, photobioreactors, attached growth systems…
7. **What harvesting techniques are required?**
   – Dewatering, drying, pulverising, bead-milling…

OUTPUT

1. **High level system architectures**
2. **Evaluation of business cases & environmental impacts**

FURTHER STEPS

1. **How should my system be designed?**
2. **How should I prototype and test my system?**
3. **How should my design be optimised for manufacture?**

These are merely the scoping questions that must be answered on the first step of the journey. As any development progresses, other key skills such as system design, thermofluidic engineering, and control are required. A breadth of multidisciplinary expertise is vital.

At Cambridge Consultants, our experts across bioinnovation, control, fluidics and chemistry have immersed themselves in the challenges and opportunities of algae cultivation. We'd be delighted to discuss the subject in more depth, and perhaps work together to help you achieve your sustainability goals. Please get in touch to continue the conversation.

Nathan Wrench, Head of Sustainable Innovation
nathan.wrench@cambridgeconsultants.com

Why us?

We can draw on deep expertise to offer a uniquely broad response to your microalgae cultivation for carbon capture challenge. Our skills and knowledge combine with real-world application experience that has been earned by multidisciplinary in-house teams.

Above all, we love to create collaborative partnerships with our clients, and are proud of our record of developing and maintaining long-lasting, mutually beneficial relationships. The team is ready to help get you where you want to be – with reduced development risk, time and cost.

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AUTHORS

Alistair MacNair, Technical Lead & Senior Chemist
Matthew White, Mechanical Fluidics Engineer
Rishi Jobanputra, Mechanical Fluidics Engineer

CONTRIBUTORS

Nathan Wrench, Head of Sustainable Innovation
Kieran Reynolds, Head of Smart Infrastructure
David Rimmer, Algorithms & Analytics Engineer
Ian Taylor, Technical Biology Lead
Luca Rossoni, Principal Biologist

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Cambridge Consultants has an exceptional combination of people, processes, facilities and track record. Brought together, this enables innovative product and services development and insightful technology consulting. We work with companies globally to help them manage the business impact of the changing technology landscape. We're not content to deliver business strategy based on target specifications, published reports or hype. We pride ourselves on creating real value for clients by combining commercial insight with engineering rigor. We work with some of the world's largest blue-chip companies as well as with innovative start-ups that want to change the status quo fast.

With a team of more than 900 staff in Cambridge (UK), Boston, San Francisco and Seattle (USA), Singapore and Tokyo, we have all the inhouse skills needed to help you – from creating innovative concepts right the way through to taking your product into manufacturing.

For further information or to discuss your requirements, please contact:

Nathan Wrench, Head of Sustainable Innovation
nathan.wrench@cambridgeconsultants.com

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