Research Into An Energy From Food Waste Scheme That Powers An Aquaponics Sustainable Food Production Business

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Originally from Scotland, Liam Devany is a mature student who returned to postgraduate education and obtained his MSc in Advanced Environmental and Energy Studies at the Centre for Alternative Technology, Wales / University of East London. His background working experience spans energy generation systems, IT, wireless communications, horticulture, vermiculture and environmental building.

He is currently in his last year of a PhD funded by the EPSRC at the University of West England, specialising in urban food production systems within the Built Environment - with a particular emphasis on apiculture. In the next stage of his post-doctoral research Liam intends to concentrate on mainstream sustainable urban food production systems which combine traditionally separate fields into closed-loop systems that have scalable potential.

He has also founded two social enterprises since the turn of the decade and is currently a director of HBC - an environmental charity that is involved with green community building projects, urban food production systems and recycling initiatives.

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Introduction

There are four main drivers that have led to this current research topic:

- Most UK Local Authorities' current attitude to the disposal of organic food waste - is to continue to send to landfill whilst space and cost permits or to incinerate
- Developments in technology are now making feasible new systems and methodologies for combining waste and food production as an integrated system
- An increase in chaotic weather systems is destabilising many parts of the environmental ecosystem and making controlled crop production unpredictable
- The aspiration to turn public perception of organic waste as a problem to one of a valuable resource.

The larger the size of a community the greater the problems it creates - such as waste generation and disposal, energy consumption, transport congestion and providing constant food supplies to the population. All produce pollution that gradually degrades the quality of life for the inhabitants.

So far, waste and energy generation plus food production have been viewed as separate areas with their own specialisations. This has led to complete stasis in planning frameworks for high density living environments. London is a good example demonstrating a lack of joined-up thinking, with different boroughs choosing very different solutions to these problems. The net result is that planning has not been visionary enough to cope adequately with waste disposal, onsite energy generation or urban food production, resulting in continuing unnecessary transport costs and subsequent CO_2 emissions.

Tackling the Food Waste Stream

Despite food waste being one of the largest single components of the UK waste stream, only 2% is collected separately for composting or anaerobic digestion [Burke, 2007]. UK food manufacturers produce around 6.2 million tonnes of food waste per annum and households 7.5 million tonnes (approximately 216 kg per household) [DEFRA, 2006]. At present 80% of this is sent to landfill and with the average cost of landfill at £65 per tonne (and rising) this equates to £712 million per year.

The reasons are complex but stem all the way from Local Authorities' inexperience in delivering a captivating message to their householders on why separating organic waste at source is good for the environment and cuts their council tax bills.

Apart from damage to the environment, throwing away uneaten food also wastes money. Current figures indicate that each week a typical household throws away between £4.80 and £7.70 of uneaten food; this is equivalent to £250-£400 a year or £15,000-£24,000 in a lifetime [DEFRA, 2006].

Food Supplies Under Threat

Ironically, whilst the UK and many other western countries are throwing away food they are concurrently facing an impending food supply shortage in the next 25 years at current rates [Viner and Wallace, 2005]. To comply with the EEC's Common Fisheries Policy (CFP) European fishing fleets reduced by 30% up to 2003 [Nautilus, 1997], which will rise dramatically as fishing stocks continue to decline. Pessimistic global forecasts predict complete extinction of our edible fish by around 2050. Stocks have already collapsed in nearly one-third of sea fisheries, and the rate of decline is accelerating. See Figure 1 below. In 2003, 29% of open sea fisheries were in a state of collapse, i.e. producing less than 10% of their original yield.

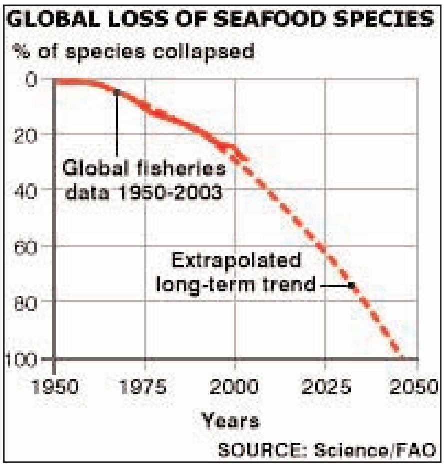
Agricultural farming also faces several threats. UK farmers supply around 90% of UK potato consumption, 70% of other vegetables, but only 10% of fruit [EAFL, 2006]. Urban population spill is consuming increasing agricultural acreage; with farmhouses becoming attractive second property buys for wealthy urbanites, making surrounding farmland redundant.

The Worldwatch Institute paints a bleak picture of erratic weather playing havoc with crop production - rearranging traditional planting and harvesting times, longer drought periods creating problems for watering crops sufficiently, alongside the type and volume of insect predation on crops [Deweerdt, 2007]. Such conditions make it difficult to guarantee crop volumes and quality, making smaller-scale arable farming increasingly less viable financially.

Precision Food Production

To counter the forecast food shortages, it will be necessary to take control of food production so that cities can adequately produce enough fish, vegetables and fruit to a consistent volume and schedule. This requires moving fish farming inland and placing vegetable crops undercover to be grown hydroponically, whilst striving to produce all food stocks organically rather than chemically (inorganic).

Figure 1: Global loss of seafood species



Fortunately, there are already established methods for doing this. In the UK, aquaculture mainly uses open-air methods to rear cold-water fish such as salmon in lakes and trout in ponds. Indoor aquaculture is rare because of the high costs of utilities, but can consistently produce large volumes of fresh water fish that prefer warm water - such as Tilapia and Barramundi.

Traditionally, aquaculture and hydroponics have been seen as separate food production processes and both have serious drawbacks with high water consumption and the toxic run-off pollutants each process generates. The most common chemical run-off constituents are calcium, magnesium, phosphates, nitrates, sulphate and potassium [Winterborne, 2005]. The reliance on these chemicals to ensure constant production results in produce, often described as bland tasting, that conforms to supermarket standards that cannot be sold at a premium price because it cannot be classified as organic.

Aquaponics

The science of combining both processes on a commercial scale is relatively new and has only established itself commercially since the 1990s. *Aquaponics* is the name coined to describe this combination: (Aqua) from Aquaculture and (ponics) from Hydroponics. It should be noted that the aquaculture aspect of this project is defined as the growing of fish in indoor tanks as opposed to cages in outdoor ponds or lakes. By combining both processes the run-off pollutants are neutralised and turned into a resource as well as being contained within a circular recycling process.

Data from areas where fishing has been banned or heavily restricted shows that protection brings back biodiversity within a zone, and restores populations of fish just outside it [Viner and Wallace, 2005]. Aquaponics can act as a respite from extensive sea over-fishing and allow alternative fish types to be introduced into the market whilst traditional stocks are allowed to build up.

Hence young fish (spry) are purchased then grown over a period of several months to optimum market size. The preferred fish is Nile Tilapia (*Oreochromis niloticus*) because of its robustness in handling changing water conditions and being able to exist comfortably in high density as it does in the wild. Tilapia is the most consumed fish globally but is unknown in northern climates as it thrives in water temperatures between 80-90°F. However, there is already an established market in the UK servicing an ethnic population accustomed to this fish - with two of the major supermarket chains (Sainsbury's and Morrison) already selling it at their fresh fish counters. Consumption of Tilapia in the Europe is expected to increase as it is relatively neutral in taste and provides a suitable substitute for traditional UK fish stocks such as cod, plaice, sole and herring as they decline over the next 20 years [Nautilus, 1997].

Tilapia is omnivorous and can be fed plants such as Duckweed within the operation [Sell, 1993]. Whether this option would be chosen would depend on the scale of the operation and the premium price paid for organically grown fish. Aquaponics requires space at a ratio of 1:7 of fish to hydroponics production [Rakocy and Hargreaves, 1993]. As the volume of space required to feed the fish organically can probably be used to grow more profitable food or pharmaceutical crops hydroponically, it is likely the farmer would directly feed fish.

The Process Cycle

In commercial aquaponics the waste generated by the fish is extracted from the bottom of the tank then held in tanks as micro organisms break down the high concentrations of nitrites to nitrates [Naylor et al, 1999], then pumped through a hydroponics growing system providing a nutrient source for vegetables and fruit. [Worthington, 2001] compared mineral levels between organically and inorganically grown crops and found the former contained less nitrates and contained significantly more vitamin C, iron, magnesium and phosphorous than the latter. Precision control of nutrients can develop new types of marketable crops. A hydroponic farmer in Virginia has developed a calcium and potassium enriched head of lettuce, scheduled for sale Spring 2007 [Murphy, 2006].

After plants extract nutrients the water it is mechanically and UV filtered then recirculated back to the fish tanks that are constantly aerated. Only 10% of new water is added to the cycle weekly, making it highly efficient in water conservation [Bugbee, 2003]. A filtered rainwater harvesting system from the polytunnel roof can be fitted in areas that have sufficient rainfall to remove reliance on mains water supplies.

A complimentary cycle is thus established, fish use oxygen and give off carbon dioxide when they breathe and their waste contains nitrogen for plants. Adding algae works in reverse as they use carbon dioxide and give off oxygen whilst using nitrogen in fish waste with light and carbon dioxide to grow. See figure 2 below.

Algal Biofuel

A proposed innovation is the integration of a process utilising the particular microscopic green algae - *Chlamydomonas reinhardtii* - commonly known as pond scum. Recent breakthroughs in controlling and increasing the algae's hydrogen yield present the possibility of it being harvested for bio diesel [Vertigro, 2006]. In this process, holding tanks are fed with fish waste nitrates and air dosed with CO_2 into enclosed photo bioreactor tanks containing light plates to enhance thick algal growth. It has been shown that the maximum productivity for a bioreactor occurs when the exchange rate (time to exchange one volume) is equal to the doubling time of algae growth [Sheehan et al., 1998].

Excess culture overflows and is harvested using micro screens. When algae is dried it retains its oil content and can then be machine-pressed to yield oil that can be converted into bio diesel, with the remaining dried fraction used as a nutrient rich fertiliser [Walker et al, 2005]. Alternatively it could be directly burned to produce heat and electricity.

The algal-oil feedstock used to produce bio diesel can be used directly for fuel as "Straight Vegetable Oil", (SVO). Whilst using the oil directly does not require the additional energy needed for transesterification, (processing the oil with an alcohol and a catalyst to produce bio diesel), it does require modifications to a diesel engine, whereas bio diesel will run in modern diesel engines unmodified. The per unit area yield of oil from algae is estimated to be from between 5,000 to 20,000 gallons per acre, per year - this is 7-31 times greater than the next best yielding crop - palm oil (635 gallons) [Sheehan et al., 1998].See figure 3 below. The system will be a continuous closed loop, which allows for a greater retention of water in the system, and eliminates cross contamination by other algae species.

Pollution Control

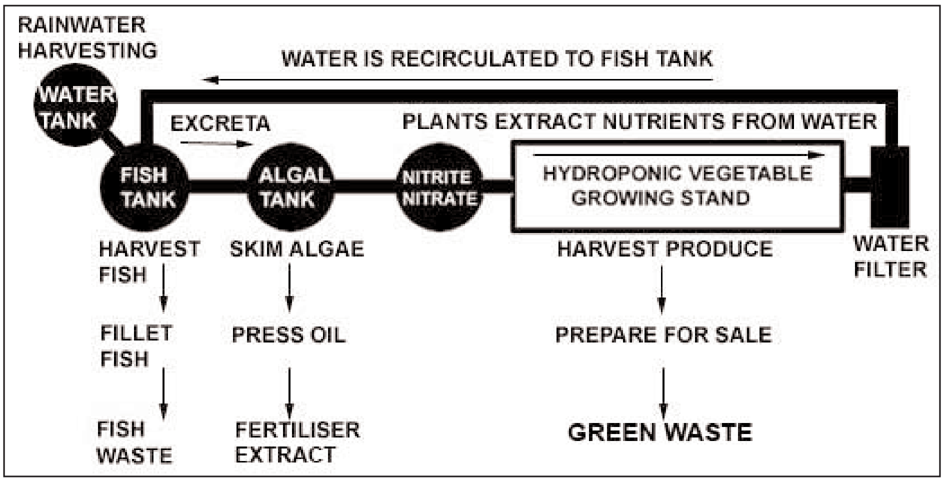
As much of the CO_2 released into the atmosphere comes from burning fossil fuels, this method provides a thorough and efficient capture by attaching a photo bioreactor to any fuel burning plant, the CO_2 produced during combustion can be fed into the algae system. With plant nutrients being sourced from fish sewage, two pollutants are thus turned into resources for the production of bio fuel, with a footprint requirement far less than other crops.

Combining Traditionally Alien Sectors

Although commercial aquaponics operations (without the algae component) can already be found in warm climates such as the southern USA, South America and Australia, they have not been able to establish themselves in northern climates because of the additional large utility costs incurred - such as electricity for lights, pumps and heating - to keep them operational. The main proposition of this paper combines an energy from waste (EFW) method with an aquaponics food / algal fuel operation to provide a "complete loop" recycling process - whilst being viable financially.

Both processing plants should be adjacent to each other to eliminate transportation costs whilst obviously retaining biosecurity standards and conforming to AFBP regulations. The feedstock is household organic food waste that is combined with waste derived from filleting fish and the preparation of hydroponics vegetable/fruit produce for sale. The EFW method in conjunction with a combined heating and power unit would service the full energy requirements (heat, cooling and electricity) of the growing operation, with excess electricity (depending on size of operation) either powering occupants homes or being sold to the grid at a premium "green" price.

Figure 2: Schematic of Aquaponics food production process, 2007



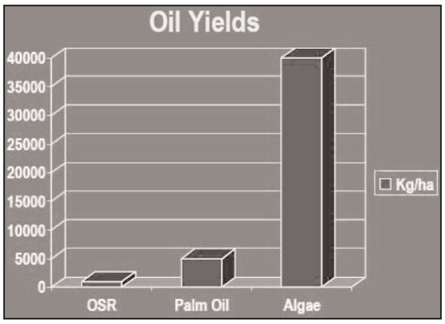
Quintuple Generation

Current technologies for EFW that are applicable are gasification and anaerobic digestion. The system can utilise quintuple-generation (QG) methods to produce biogas, heat, refrigeration, electricity & bio fuel to maximise energy and food output most efficiently. QG's superior efficiencies surpass "state-of-the-art" combined cycle cogeneration power plants by up to 50% [Goodell, 2007]. Coupled with a 4-pipe system, this process produces hot water/steam and chilled water simultaneously, for circulation throughout a high-density building or village. By integrating refrigeration into the system fresh fish / vegetable stocks can be chilled or frozen whilst awaiting consumption.

Size is not an impediment, as any scale will still remain at system efficiencies of 90% [Soderman, 2002]. A system integrated into urban/commercial buildings could pay for itself in just 2 years, depending on local electric rates, natural gas (or other fuel) costs, and the load profile of the building.

There follows a brief discourse outlining the benefits and disadvantages of the two main EFW processes for treating food waste, although it must be noted that very few plants currently in operation are exclusively processing food waste.

Figure 3: Oil yields © NREL, 1998



Anaerobic Digestion (AD)

AD is the preferred solution for smaller operations on a cost basis. A temperature-phased digester combines two types of digestion technologies (mesophilic and thermophilic) into a two-stage reactor, increasing methane yields. In general, operations servicing more than 450 people (150 households) are able to benefit from economies of scale, with installation costs around £200 - £250 per head [Davidsson et al., 2007]. Previously, systems without waste heat recovery used around 30% of the biogas they produced to heat their own digestion process. The energy content of the waste heat must be high enough to be able to operate equipment typically found in trigeneration power and energy systems such as absorption chillers, aerators, heat amplifiers, dehumidifiers, hot water heat pumps, turbine inlet air cooling and other similar devices.

Although more expense in householder education is required for separation of organic waste at source, the capital set-up costs are less compared to thermal based methods. Such an installation would be appropriate for small communities or large tower blocks - where integration into the building is the preferred route. The food, algae and rainwater harvesting is located on flat roofs under lightweight polytunnel structures to maximise sunlight exposure and conserve energy requirements.

Meanwhile food waste moves down the building in gravity chutes to the AD plant located in the basement. The gas produced powers turbines, and a CHP unit utilises the heat generated for the living quarters and the food growing operation on the roof. Good sound insulation (highest sound emissions occur in the encapsulated generator and amount to around 80 dB (A) at a distance of 1 metre), efficient fraction separation and odour control are the technical challenges in this type of installation.

Conversion of this biomass into combustible gas also has all the advantages associated with using gaseous and liquid fuels such as: clean combustion, compact burning equipment, high thermal efficiency and a reasonable degree of control.
AD harnesses and contains naturally occurring process of decomposition to treat the waste and produce biogas that can be used to power electricity generators, provide heat and produce soil ammendments. A temperature-phased digester combines two types of digestion technologies (mesophilic and thermophilic) into a two-stage reactor, increasing methane yields. In the UK, five plants were currently operational and another six in various planning stages at the end of 2006 [AD, 2006] but none within buildings.

AD has three main applications for built environments:

- It's a proven waste disposal technology which appeals to Waste Authorities as they enter contracts to build new waste management facilities
- Agricultural Waste Management and production of fertiliser and on-farm biogas
- Renewable energy generation assuming current (Spring 2007) energy prices are maintained.

If the 5.5 million tonnes of UK municipal food waste were targeted for separate collection, then the total quantity of electricity generated would be in the region of 477-761 GWh per annum if the material was digested. This is equivalent to the electricity used by between 103,000 - 164,000 households, or 16-26% of the energy generated by wind power in the UK in 2005 [Keay, 2005]. Composting the same amount of material would utilise energy in the process.

The net position in respect of greenhouse gases is likely to be such that routing the material through AD rather than composting will improve the position in respect of greenhouse gases in the region of 0.22 - 0.35 million tonnes CO_2 equivalent (based on an assumption that the displaced source is gas fired electricity generation). If equivalent biomass had been land filled, savings increase to 1.6 - 3.6 million tonnes CO_2 equivalent, depending upon the performance of the landfill and the digester.

Benefits of Anaerobic Digestion

- Because the process is contained, odour is controlled, which can help meet permitted limits on emissions
- AD destroys more volatile organic compounds and produces more gas than traditional composting methods used e.g. for the treatment of sludge
- AD produces less solid waste, and what is produced can be used directly on fields as a mulch or soil amendment
- Biogas collected from the process can be used to offset energy costs by providing heat, running refrigeration, supplying process heating and producing electricity and steam
- Using biogas reduces fossil fuel dependence thus reducing pollution generated by drilling, mining, transportation and emissions, including methane and CO_2.

Disadvantages of Anaerobic Digestion

- Purchase and installation is more expensive than closed windrows
- Additional plant, time and labour are required at the front end to ensure purity of the feedstock. Any plastic or synthetic material contamination can shut down the AD flow
- Requires water supplies - although some water costs can be mitigated via a good rainwater harvesting system
- Although the plant requires a relatively small footprint, labour and space for separating incoming waste can be considerable
- Although not as foul as closed windrows, the odour surrounding an AD plant is still unpleasant to work in.

Pyrolysis

The other route to utilising food waste for EFW is a thermal conversion process carried out in the absence of oxygen, yielding solids, liquids and gases. Within the context of electricity generation, slow pyrolysis that yields a carbonised product can be used as a pre-treatment step before gasification. The intermediate product has well defined characteristics, offering several options for power production.

Pyrolysis of waste is mainly carried out as a pre-treatment for high temperature combustion or gasification processes. Due to the uniformity of the carbonised product, better control of the thermal conversion process is possible. As costs drop for cleaner and/or precision controlled systems in the medium to long-term, the importance of pyrolysis as a pre-treatment step is likely to increase.

Gasification

This occurs when a solid or liquid substance is transformed into a gaseous mixture by partial oxidation with the application of heat (pyrolysis). The process is optimised to generate the maximum amount of gaseous breakdown products, typically carbon monoxide, carbon dioxide, hydrogen, methane, water, nitrogen and small amounts of higher hydrocarbons. If all the UK's food waste was processed through pyrolysis/gasification methods it could generate up to 6 billion kW hrs of energy - which equates to enough energy to power 1.3 million houses per year (based on UK average consumption figures) [Atari, 2004].

Its prime advantage is it can flexibly manage contaminated feedstock. Packaging, along with various organic fractions, can be directly fed into the process without pre-separation. This saves on labour costs and storage space and makes collection an easier proposition for local authorities, with little education of the householder required. It is also a more suitable EFW method for large food manufacturing/sales operations required to dispose of out-of-date products from supermarkets compared to the costs of separating organic waste from packaging using AD.

Disadvantages

Whilst gasification is a process optimised for the maximum yield of gases, it still generates solid and liquid by-products as a result of the reduction of organic matter, which may contain high levels of toxic contaminants. A previous review of pyrolysis systems by CADDET (1998) raised concerns about residues from these processes. Mohr et al. (1997) found that dioxins and furans were formed in the cycle producing high levels in liquid process residues. Weber and Sakurai (2001) examined the formation of dioxins and furans under pyrolysis conditions and concluded that they were definitely formed from wastes containing chlorine and copper. However, contemporary thermal treatment process plants with effective gas scrubbing can reduce the emissions of acid gases, heavy metals and dioxins and furans to levels well below the EU Waste Incineration Directive emission limits.

Capital costs are therefore significantly higher at the backend, with extra plant required to deal with NO_x and toxic wastewater. It's likely much of this "cleansing" equipment may not be required when supermarkets and food suppliers move over to 100% biodegradable point of sale packaging, e.g. biodegradable cardboard with cornstarch windows packaging. At that point reduced costs of smaller-scale gasification/CHP plants would allow installation in the basements of large municipal buildings and housing blocks. Until then the costs for this process will remain higher than AD.

Gasification stands or falls by how it handles its waste by-products. It is currently more appropriate as a large-scale EFW technology that closely follows the traditional centralised collection model utilised by combustion power stations for over fifty years. Allied to a large-scale aquaponics operation located alongside this plant, economies-of-scale and productivity benefits will be considerable. The necessary plant distance from urban centres means there are no savings on transport fuel costs compared against existing food and waste collection and distribution methods.

Environmental Benefits

Aquaponics, AD and gasification methods have the benefit of offsetting the use of fossil fuels such as coal and natural gas. As the waste materials processed are organic matter, they can be considered carbon neutral and their diversion from landfill also reduces land and water pollution and prevents the release of methane - which is 22 times more atmospherically damaging than CO_2. By using this process it is estimated that landfill methane emissions could be reduced by many metric tonnes of carbon, equivalent to having planted (x) acres of forest or removing the annual emissions from (x) cars.

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