Paper 2 – To what extent is UK CEA pursuing synergies with waste streams from the urban context and what are stakeholder opinions regarding this, in the UK CEA sector and at the city level, in Bristol

Abstract

Stakeholders in the UK's indoor farming sector were interviewed to determine if waste resource streams from the urban context are being utilised for circular economy benefits. They were found, generally, to be open to synergies with waste heat and waste energy streams, though only one example was identified, and to rainwater collection where roofs were large. They had little interest in waste CO_2 or waste nutrients because their use lacked economic drivers or marketing advantages and introducing recycled inputs into CEA increases complexity and risk of failure. Further research on using organic nutrients in hydroponics would be useful. Stakeholders in Bristol's energy, waste and food sectors were interviewed to determine attitudes regarding such synergies. Little interest in CEA was found and waste management is focused on reducing carbon emissions. Future research could investigate more holistic methods of evaluating use of urban waste streams, to include wider social, environmental and health issues, instead of just carbon.

1.0 Introduction

1.1 Background

This research arises out of the debate on the potential for urban based controlled environment agriculture (CEA) to help address three key global challenges of this century, of rising food demand, increasing urbanisation and pressures on world resources of unsustainable consumption. Population is predicted to rise 2 billion to 9.7 billion by 2050, (UN, 2019a), which, together with increasing meat and dairy consumption due to rising incomes, will increase global food demand by around 70% (Bruinsma, 2009), whilst natural resources and agricultural productivity are being negatively impacted by climate change in much of the world, (Shukla et al., 2019). Meanwhile, increasing urbanisation, estimated to be 68% by 2050, (UN, 2019b), is reducing food security in many countries, (FAO, 2017), whilst current global consumption levels exceed the planet's carrying capacity, (Rockström et al., 2009), requiring the adoption of more efficient resource use practices, as called for under SDG 12 (UN, 2020).

Urban agriculture (UA) refers to any kind of food production in the urban context, including not just CEA but also open air agriculture on roofs, balconies, backyards, waste land, etc. UA has been promoted as having potential to help address these problems. Claims include that UA can help reduce agriculture pressure on natural habitats, reduce food miles through shorter supply chains, improve food security in urban areas and provide social, community and mental health benefits, (Al-Kodmany, 2018; Benke & Tomkins, 2017; Despommier, 2013; Goldstein, Hauschild, Fernández & Birkved, 2016; Pinstrup-Andersen, 2018; Specht et al., 2013).

People have traditionally lived close to agriculture allowing waste products to be recycled as agricultural inputs. Growing urbanisation is increasing the linear consumption of resources, with massive one way transfers of energy and nutrients from rural areas into the city. Waste streams containing nutrients must then be treated and disposed of, much of which may be lost to incineration, landfill or water courses, (Morée, Beusen, Bouwman & Willems, 2013; Kalmykova, Harder, Borgestedt & Svanäng, 2012). Recovering and recycling nutrients from waste streams is likely to become increasingly important if mineral reserves of critical nutrients such as potassium and phosphate become more difficult to access, (Heckenmüller, Narita & Klepper, 2014).

UA can potentially create new synergies between food production and urban populations, making it possible to utilise the waste heat, energy, water and CO_2 streams from buildings and urban facilities and the embodied energy and nutrients contained within solid or liquid urban waste streams, such as sewage or food waste, to create a more circular, sustainable, agricultural model, (Goldstein, Hauschild, Fernández & Birkved, 2016; Martin, Poulikidou & Molin, 2019; Mohareb, 2017; O'Sullivan, Bonnett, McIntyre, Hochman, & Wasson, 2019; Specht et al., 2013; Thomaier et al., 2014). Potential synergies are summarised in Table 1.

Table 1. Summary of potential synergies between indoor farming and urban waste streams

Synergy Type	**Waste Streams**
Waste Energy Flows	A range of heating and cooling plant normally supply modern buildings. These reject waste streams of heat or "coolth", often at roof level. This can be captured by a farm located in or adjacent to the building. Facilities such as data centres, industrial plants, power plants and sewage works may also generate significant flows of waste heat which could justify collocating a farm nearby to utilise the heat energy. Combined heat and power (CHP) plants will also produce waste heat and CO_2 byproducts which can be used by the indoor farm. Waste to energy (WtE) power plants can convert urban generated waste for use by urban farms. Options include: • Diversion of non-recyclable urban waste from landfill for gasification. The resultant syn gas can be used to generate electricity or for heating. • Processing of organic urban food waste in anaerobic digesters (AD). The resultant gas can be used for power generation or heating. Food waste sources could be domestic from kerbside collection, or commercial, from restaurants, supermarkets, breweries/distillers, food processing factories, etc.
CO_2 **Flows**	CO_2 enrichment of the growing space is a key factor in achieving high yields. It is typically a byproduct of fertiliser production. Alternative sources include: • Anaerobic digesters • Waste by products of fossil fuel combustion related to industrial processes • Brewing and distilling
Nutrient Flows	Possible sources of waste nutrients include

Synergy Type	Waste Streams
	• Sewage sludge • Food waste • Digestate from anaerobic digesters • Various forms of composting, including vermicomposting
Water Flows	Offsetting the farm's water supply by rain water harvesting (RWH), or by treating the building's grey water is possible.
Integrated Rooftop Greenhouses (iRTG)	An iRTG is an RTG integrated into the building's metabolism, allowing mutually beneficial synergies with its partner building. Possible synergies are described below.
	Active Systems By integration with the building's air circulation system. • Heat transfer between the iRTG and the building, to warm the iRTG or the building. • Transfer of oxygen enriched air from the iRTG to the building and of CO_2 enriched air from the building into the iRTG
	Passive Systems iRTGs can provide insulation to reduce winter heat loss and summer heat gain to the building, whilst the thermal mass of the building can help warm the iRTG during night time.
	CO_2 Enrichment By CO_2 capture from flue gases from the building's boiler system.
	Irrigation Water From captured rainwater or by treating the building's grey water.
References	(Goldstein, Hauschild, Fernández & Birkved, 2016; Martin, Poulikidou & Molin, 2019; Milford, Kårstad & Verheul, 2019; (Mohareb, 2017); O'Sullivan, Bonnett, McIntyre, Hochman, & Wasson, 2019; Pons et al., 2015; Sanye-Mengual et al., 2018; Specht et al., 2013, Thomaier et al., 2014;).

CEA, the focus of this research, is a protected form of UA where the growing environment can be modified and controlled. It ranges from simple ground or rooftop greenhouses to sophisticated, high tech, close controlled, automated, vertical plant factories, the latest acronym for these being TCEA or total controlled environment agriculture. Growing methods are usually soilless, although ground based glasshouses may often use soil. Soilless techniques include hydroponics, aeroponics and aquaponics.

Vertical farming (VF), by using the complete volume of the enclosed space for growing, can achieve much greater yields per square metre, especially with artificial lighting and optimisation of indoor growing conditions, whilst also having more efficient nutrient uptake, reduced water consumption and reduced pest and disease risk. Additional benefits year-long growing seasons, supply of consistent high quality clean produce and reduced food waste due to the uniform produce quality and reduced pest and disease incidence, (Al-Kodmany, 2018; Benke & Tomkins, 2017; Goldstein, Hauschild, Fernández & Birkved, 2016;).

However, these benefits come at the expense of high equipment costs, high energy consumption to supply artificial lighting and space cooling and high labour requirements. (Agrilyst, 2017; Agritecture & Autogrow, 2019; Goldstein, Hauschild, Fernández & Birkved, 2016; Graamans, Baeza, van den Dobbelsteen, Tsafaras & Stanghellini, 2017; Hughes, 2018; Savills, 2019). This challenges profitability of the concept and raises questions over the its economic and environmental sustainability.

1.2 Research Aims / Statement of the Problem/Research Gap

Mutually beneficial synergies with urban waste streams, as summarised in Table 1, could improve urban sustainability whilst also cutting CEA running costs but few documented examples were identified during the literature review (Mugford, 2020). This research was therefore initiated to discover the extent these synergies are being adopted in the UK and the barriers and challenges to achieving them. Additionally, it looks at resource use management in Bristol to see if there is any existing trend or policy to pursue these synergies with CEA. Bristol was selected as the focus of this study since it has been active in promoting sustainable food systems and sustainable change, reference their awards of

European Green Capital 2015 and Silver Sustainable Food City 2016 and their commitment to become carbon neutral by 2030, (Bristol One City, 2020b).

Research was carried out by interviewing key stakeholders in the UK indoor farm sector and the Bristol energy, waste and food sectors to discover their opinions and experiences on these issues.

1.3 Scope Limits

Renewable energy supply and circular resource use involving agricultural waste products could improve CEA sustainability but these are not a focus of this research since they do not involve urban waste streams.

The research was undertaken during the lockdown period in the UK which limited data collection to phone calls instead of farm visits and face to face communication. However, it was still possible to obtain quality information and draw appropriate conclusions, so it is believed that the analysis provides a fair representation of the situation in the UK today.

The research focuses on commercial urban indoor farms. Farms at educational institutions, e.g. the Plant Factory at Plymouth University, are not considered. However, horticultural glasshouses are included where relevant, since there is much crossover with urban CEA, although the sector has not been studied in detail. Refer section 3.1.1 for more details. The research does not exclude non-urban CEA, since a rural location may not preclude synergies with urban waste streams, as the example with Low Carbon Farming, described in section 3.2, shows.

The paper makes no attempt to evaluate whether utilising urban waste streams for indoor agriculture is in fact the most sustainable use of that resource. It may be that other criteria should have higher priority, such as achieving greater carbon emission savings. This is also discussed in section 6 with regards to Bristol and may be a suitable field for further research.

2.0 Research Methods

2.1 Introduction

This research aims to investigate the extent to which synergies between CEA and waste streams from the urban context are being realised in the UK today, the barriers and challenges to achieving them, and secondly, the situation in Bristol regarding resource management to facilitate such synergies.

It was decided to gather data by interviewing the main stakeholders in these sectors regarding their experiences and opinions. This data would be collected in as systematic and objective a way as possible, analysed and would then form the basis of any conclusions that could be drawn.

2.2 Interview Method

Interviews were by semi-structured, one to one phone calls. Interviews were informal and conversational, allowing time to understand each participant's perspective and experiences, to probe their statements in more detail and to develop deeper insights.

Based on an understanding of the topic derived from the literature review, (Mugford, 2020), the following basic interview structure was developed to ensure that each interview covered similar ground and comparable data could be collected:

(1) Introduction of myself and the research topic
(2) Discuss the interviewees' background,
(3) Discuss their operations/interests
(4) Discuss the market in which they operate
(5) Discuss synergies and their opinions/experiences of these
(6) Additional discussion

Interviews were conducted by phone and written up immediately afterwards. The notes were then shared with the interviewee giving them the opportunity to verify the points or clarify further. They were then analysed and conclusions drawn from them.

A few challenges were noticed with this approach, mainly that of overcoming resistances to participate. VF attracts enormous interest, from the media, academics, and local education institutions and operators are sometimes overwhelmed by requests for their time, which can be a challenge to manage. Interviewees might also be reluctant to share details of their own technical solutions, market models and upcoming business opportunities due to confidentiality concerns. Additionally, in this form of research there is a necessity to guard against bias, to avoid asking leading questions or interpreting the answers in a biased way.

2.3 Selection of Interviewees

Individuals with experience or interest in the UK CEA sector and in Bristol's food, energy and waste sectors were sought for interview, located by internet searches and snowballing techniques.

3.0 Results

3.1 Introduction

3.1.1 UK CEA Sectors

Feedback from the interviews revealed that UK CEA comprises a number of sub-sectors, which are summarised in Table 2.

Table 2: Summary of UK CEA Sectors

Type	**Details**
Rooftop greenhouses (RTG) or integrated rooftop greenhouse (iRTG)	Soil or soilless with varying complexity of integration into its partner building.
Enclosed vertical farm	Dependent on artificial light. Ranges from small scale operations, of varying degrees of sophistication, generally supplying local premium price markets, often local restaurants, to larger scale high tech operations with high levels of automation and environmental control, connected to sophisticated national supply chains.
Sunlit ground based glasshouse / poly tunnel	Conventional horticultural glasshouse
Hybrid glasshouse / poly tunnel	Utilising vertical or ground based techniques, soil or soilless, heated and non-heated, and CO_2 enriched or ambient
Insect farms	Require heated growing spaces and organic feed.

The horticulture glasshouse sector was not originally intended to be included in the research, being neither urban based nor utilising controlled environments, but rather just protected agriculture. However there seems to be increasing crossover and growth in a hybrid sector where glasshouses and poly tunnels employ CO_2 enrichment, supplementary lighting, temperature control and even VF techniques, so it became difficult to exclude them from the analysis. As clarified by several interviewees, the glasshouse sectors tend to operate at scale, often with units of around 10,000m^2 or more. Vertical growing techniques under glass are restricted to a certain height beyond which artificial lighting must be provided. Supplementary artificial lighting might also be provided to boost growth during critical phases or to extend the growing season.

3.1.2 The Interviews

30 interviews were conducted between May and June 2020 with CEA stakeholders and 6 interviews plus one email correspondence were carried out between June and July 2020 with stakeholders in Bristol. Interviews took on average around 40 to 60 minutes. Interviewees are summarised in Table 3 below.

Note that some interviewees act in more than one category, for example as both a grower/operator and as a technology provider, so totals exceed the number of interviews. After conducting a certain number of interviews, it became clear that no additional data was being raised on a certain topic, leading to the assumption that a large enough sample size had been reached.

Table 3: Summary of interviews carried out

Type	Category	No. Interviews
UK CEA Sector		
Rooftop greenhouses	Owner / Operator	1
	Architect/Consultant	2
	Start up	1
Ground based glasshouses/tunnels, including hybrids	Developer/Technology Provider	2
Scaled Indoor artificially lit farms	Investor	1
	Developer	1
	Technology Provider	4
	Operator	2
	Start-Up	3
Small local indoor artificially lit farms	Operator	7
Insect farm	Operator	3
Aquaponics	Academic	2
Journalist/Lobbyist/Analyst		2
Academics		2

Type	Category	No. Interviews
BRISTOL FOOD, WASTE AND ENERGY SECTOR		
Food Systems	Consultant	1
	Community Organisation	Email correspondence
Waste to Energy Sector	Collector	1
	Consultant	1
	Treatment Plant Operator	2
Energy Sector	Operator	1
Other	Consultant in urban resource mapping	1

3.1.3 Analysis Method

The analysis is split into 2 parts as per the two parts of the research question. This analysis has then been subdivided by synergy type or CEA type, as appropriate. Key findings of the interviews are summarised in 3.2 and 3.3 below.

3.2 Synergies with CEA

Only a few examples of synergies were found, which are summarised in Table 4. Barriers to adoption, as advised by the interviewees, are discussed in section 4.

Table 4: Summary of synergies found between UK CEA and urban waste streams

Synergy	Details
iRTG	**Roof Top Greenhouse on Private Building – already demolished** Built in Hackney, London, in 2010, on the roof of a residential home cum office. Integrated into the building's heating/ventilation system so warm greenhouse air was supplied to heat the space and then recirculated back to the greenhouse.

Synergy	Details
	Controlled by temperature sensor and fan speed control. Greenhouse air humidity was removed from the living space by a heat pump. The owner felt that the IRTG contributed around 80% of the house's heating demand, being especially effective during spring, autumn and sunny winter days, although occupancy was too low for CO_2 levels in the return air to be beneficial to the IRTG. Converted to a working study after 5 years due to lack of any traction/interest in the concept, the hard work growing the crops and since the space could be better used for something else.
	Ilford Community Market – pre construction stage. Designed in 2019-2020. Not yet constructed. Concept: Food grown, sold and consumed on site. Greenhouses are located on the roof above a newly constructed food market selling fresh produce and prepared meals. The design includes the following: An AD to process on site generated organic waste, with byproduct gas used to heat the building and digestate used to return nutrients to the growing space. Provision for future RWH to supply water to the farm, subject to budget. It is not known whether CO_2, recovered from the AD, will be supplied to the polytunnel. The market lacks an enclosed space so the concept of integration with the ventilation system is not possible.
	Automated hydroponic greenhouses located at point of need – concept stage Hydroponic, vertically farmed, short cycle crops in a glasshouse on top of the building where the crop would be purchased or consumed, e.g. a supermarket or office building. Now in post prototype stage, seeking funds and sites. Benefits of integration, in the proponent's view, could include exchange of warm and cool air and oxygen and CO_2 enriched air between the IRTG and the building, capture of waste heat from the supermarket's HVAC (heating,

Synergy	Details
	ventilation and air conditioning) and refrigeration plant, reduced heat loss due to the insulating effect of the IRTG, use of reject CO_2 from the kitchen boilers and use of the roof as a rainwater and solar collector, to supply the IRTG.
Urban Waste Heat Streams	**Low Carbon Farming:** Colocation of 29 ha of hydroponic tomato glasshouses next to 2 Anglian Water STPs, (sewage treatment plants), located in Norwich and Bury St Edmunds. Currently under construction. Greenhouses will be heated by waste heat. The waste heat is sourced from the treated effluent discharges from the STPs and extracted by heat pumps. The treated effluent discharges are 4°C above the nearby river water temperature. Heat pumps and the farms will be run by power generated by mains gas fired CHPs. By-product CO_2 and heat from the CHPs will also be supplied to the glasshouses and any spare power will be supplied to the grid. An additional benefit is the final effluent temperature is reduced, thus benefitting the local river ecosystem. The project is made possible by qualifying for the government's renewable heat incentive (RHI) scheme. The investor advised they are looking for similar projects in the time left before the RHI scheme is closed in 2021 and in June 2020 they announced a second similar project in north Wales, involving 2 nos. 7.6 ha glasshouses, at Dyr Cymru's Five Fords STP.
	Cornerways, Wissington, Norfolk An 18 ha. glasshouse development was built next to British Sugar's sugar beet factory to use waste heat and CO_2 from their CHP plant, (Rackley, 2016)
	Colocation with Data Centres

Synergy	Details
	One interviewee mentioned a proposed CEA project, currently under negotiation, to co-locate with a data centre to utilise the centre's waste heat, although details were still confidential. Similar projects are ongoing in the Netherlands where, for example, Alphabet and Microsoft will construct large data centres in an agricultural zone and supply their waste heat to the glasshouses. (Iamsterdam, 2019).
Energy from Urban Waste	Two interviewees were actively pursuing co-location with low cost WtE operators, to reduce operating costs.
	In a similar vein, a few others were looking at purchasing renewable energy from solar or wind farms to both cut costs and for the lower carbon footprint narrative, although without utilising urban waste streams.
Waste Steams from CEA	Existence of VFs colocated with a brewery and a distillery were found, although it was impossible to contact them, presumably due to interruptions caused by Covid. It is understood from internet searches (Urbanagnews, 2019) that at Vertivore, the resource flow is in the opposite direction, with waste heat from LEDs being used in the brewing process. It is not known whether waste CO_2 from the brewing process is transferred to the growing area.
Waste CO_2	CO_2 is a waste byproduct of CHP plant and ADs and is often supplied into horticultural glasshouses, as mentioned above at Cornerstones, (Rackley, 2016).
Water	According to operators' websites, many horticultural glasshouses employ RWH, to capture rain from roofs to reduce water consumption, (Cambridge HOK, 2020; Thanet Earth, n.d). One large scale VF stated they operated a RWH system One technology provider includes an optional RWH system design n their package.

Many ground based glasshouses utilise CHP plant to supply heat, power and CO_2, often also supplying the grid (Cambridge HOK, 2020; Tangmere, 2020; Thanet Earth, n.d;). These could operate on urban waste streams but no such operations were discovered during this research. Glasshouse CHPs seem, based on an internet searches and interviews, to be run on mains gas or agricultural biomass and so don't represent a synergy with urban waste streams. The above mentioned projects involving Anglian Water, as far as could be established, are unique in this context, where the waste heat is generated from wastewater flows from urban populations.

The immediate conclusion drawn from the above is that practical synergies seem to be limited to colocation with low cost WtE providers to utilise the power, waste heat and waste CO_2, or to colocation with buildings or facilities with large waste heat flows, whilst RWH tends to be adopted in operations with large roof areas. There were no examples of utilising nutrients from urban waste streams, or of grey water and CO_2 from the built environment.

The synergy between CEA and brewing interestingly was in the opposite direction and this could be a significant benefit to the co-located building/operation.

3.3 Bristol

A review of relevant documents related to planning for a more sustainable Bristol and discussions with stakeholders revealed a strong commitment in Bristol to achieve efficient circular economies in resources use and to maximise UA. However, there was little mention of CEA and little interest in synergies between CEA and urban waste streams.

4.0 Discussion – CEA Synergies

4.1 Introduction

As described in section 3.2, the data suggest that the most practical synergies with urban waste streams are colocation with WtE providers, colocation with buildings or facilities with large waste heat flows and RWH. Other synergies are generally not being pursued. The challenges and barriers to these data are analysed further in the following sections. The discussion is generally subdivided by synergy type, although IRTGs and insect farms are discussed separately.

Feedback from the interviews suggested that the UK CEA industry is currently in a state of flux, with many failures, many newcomers and rapid technology developments. It is therefore appropriate to first summarise some key issues raised by the interviewees regarding the industry, before going on to discuss the synergies.

4.2 Current State of the Industry

Two interviewees remarked that CEA uptake in the UK is relatively slow, mentioning the lack of factors such as higher food prices, scarcer land supply, unsuitable weather conditions for outdoor growing or long transportation distances, which have helped stimulate growth in the CEA sector in countries like Japan, UAE, Singapore and USA,.

Challenges in operating in the UK were mentioned by many although the consensus was that commercially successful CEA is possible as long as the “ecosystem” of the model, as one interviewer put it, is correct, i.e. farm location, source and costs of the inputs, crop type, market and distribution system must all be appropriate. The interviews revealed many unique and compelling takes on the CEA concept and there is no one size fits all solution. However, most interviewees proposed similar reasons why CEA had not yet taken off, that of high energy and labour requirements, high start-up costs and low food prices. High urban land costs, problems in accessing finance and challenges in scaling up were also mentioned.

An interesting topic is the question of government support, which was raised by several interviewees. Conventional agriculture benefits from payments through the EU’s CAP, (to be replaced soon), subsidised fuel and lower business rates. These do not apply to CEA. Additionally, many glasshouse operators subsidise their operation by generating power to sell to the grid or qualifying for government RHI payments, which as some advised, may be more valuable than the produce being grown. However, most interviewees felt that it was important the sector should be self-sufficient and sustainable without government support.

More positively, many believe this is an interesting time in the CEA sector's development, as technology developments start improving the economic basis of operation, allowing a greater range of crops at more competitive prices. Developments include greater automation, improved LED and nutrient transfer technology, more intelligent environmental control and more energy efficient HVAC systems, all optimised by machine learning. One interviewee also expected developments in plant breeding in the next 5-10 years would create varieties better aligned to indoor farming, promising big improvements in yield.

Many of the interviewed high tech operators and tech providers are claiming that parity in running costs with heated glasshouses is, or soon will be, achievable whilst their greater crop density allows higher yields per farm footprint, although this was not a universally held opinion. However, this may be a factor behind a series of high profile investments in the sector in the last 12 months, including for Vertegrow, (The Press and Journal, 2020), Jones Food Co., (BBC, 2019), Shockingly Fresh, (Shockingly Fresh, 2020). Vertical Future, (Holder, 2020), Vertivore, (Johannak, 2019), Lettus Grow, (HortiDaily, 2020), and IGS, (Gan, 2019).

Similar developments are affecting the glasshouse sector, with improvements in heating and lighting, glazing materials, automation and robotics, ((Cambridge HOK, 2020).

4.3 Energy

<u>4.3.1 Introduction</u>

Heat is necessary to maintain temperatures in greenhouses whilst artificially lit VF's need power to run lighting and automation systems, cooling systems to remove heat generated by the lighting and ventilation and humidity control systems. Most VF interviewees believed that energy costs were the key challenge to profitability, several stating that models could not be feasible if run on grid power, although some, including a couple of the technology providers, believe increased efficiencies through technology improvements were close to bringing this under control. In fact, one technology provider considered labour and real estate costs a bigger challenge than energy costs. However, any methods to reduce the cost of energy would obviously improve the bottom line. Two options for energy synergies with urban waste streams were identified, using waste heat streams or using cheap energy generated from urban waste streams.

4.3.2 Waste Heat Energy from Buildings or Other Facilities

Interviewees from the TCEA sector commented that waste heat is unlikely to be useful, removal of heat generated by LEDs being more the challenge.

However, some VF operators felt they still need heating during the winter and many glass or poly tunnel based operations rely on it. In fact, the only examples of synergies found involved glasshouses, reference the colocation with STPs (Low Carbon Farming's venture with Anglian Water), and with industrial processes (Cornerways Nursery and British Sugar), plus a potential project still under discussion, with polytunnels colocated with a data centre.

Such synergies would require reasonably close co-location to the source of the heat or energy, to avoid losses and reduce investment costs although it is noted that the Low Carbon Farming greenhouses are actually 2km from the STPs.

Finding the right heat or energy source and suitable land nearby obviously will present a challenge, especially for models where being close to local markets or being close to distribution hubs is also important. This was a barrier mentioned by Wessex Water to adopting the same in Avonmouth, as discussed in section 5.

The synergy examples found in the UK involve large farms and large infrastructure investments. These models would not be applicable to smaller scale local CEA, as some of the interviewees mentioned. Smaller operators commonly referred to their need for reliable control of heating and cooling and the small margins they operated under. Integrating with neighbouring waste energy streams would require investment, may not be logistically easy and would increase complexity and risk of failure.

4.3.3 Low Cost Energy from Conversion of Urban Waste Streams

Colocation around a low cost WtE hub, either using gassified non-recyclable waste or organic waste converted in ADs, was also discussed. There are additional beneficial synergies to this since waste heat and CO_2, generated in the production of the electricity, could also be utilised by the farm.

Most interviewees seemed to support the idea. No existing examples were found, although one developer mentioned they were looking at possible sites where colocation with low energy providers would be a beneficial add on and one start up model was based on this concept.

A couple of caveats were raised regarding this though. One investor reported being unable to find profitable opportunities based on urban VFs linking to waste energy from local urban ADs. Indeed, a regular comment was that cheap energy sources are not common in urban areas, making this option more applicable to peri-urban or rural areas, whilst bulky solid waste transportation from urban areas would be costly. Several also noted the risks of building a business model whose viability is reliant on a third party energy supplier's continued operation. This would put off prospective investors. This point is also applicable to section 4.3.2 above. Risks of signing long term agreements to take a fixed amount of energy was also remarked. The business model must stand up without this, although the upside benefits would be welcomed.

A common concern amongst interviewees with this synergy was over contamination issues, caused by proximity of food production to waste collection and treatment facilities, though this risk may be more perceived than real.

4.3.4 Waste Energy Flows from CEA

Two options for dealing with waste heat from LEDs in indoor CEA was discovered, based on internal and external reuse. Co-location with a brewery allowed the waste heat to be reused in the brewing process. Conversely, some technology providers and large scale CEA operators, mentioned that their systems included innovative energy recovery systems enabling capture and transfer of the LED waste heat into their HVAC systems, and that this is essential to reduce energy costs.

4.3.5 Buildings as Sun Collectors

A few interviewees expressed interest in installing solar PV cells on their roofs to offset energy costs and to gain a sustainability narrative. Cost barriers meant none interviewed had yet invested in this and of course, the generating capacity that could be fixed to a building façade would be insufficient to run an indoor farm, (Benke & Tomkins, 2017).

4.4 Waste CO_2

CO_2 enrichment can be a key factor in achieving high CEA yields. CO_2 in the UK is typically a low value byproduct of ammonia/fertiliser production, (Global Counsel, 2018). Recovering waste CO_2 from existing urban combustion streams, for example from a building's existing space heating system is possible, although a more carbon neutral method would be to use CO_2 derived from WtE plants, as mentioned in section 4.3.3 above.

It was noted that not all operators adopt CO_2 enrichment, especially smaller scale VF operations, but also many glasshouses. Use of waste CO_2 from CHP plant in the glasshouse sector was common though, although, as discussed in section 3.2, these CHP are generally run on natural gas or biofuels.

A number of interviewees mentioned that CO_2 is not a costly input so there is no economic driver to pursue this synergy, other than the sustainability narrative, whilst a recurring theme from many interviewees is that it's the supply of locally produced clean and nutrition produce that drives the CEA market and achieves the premium prices, rather than the sustainability narrative (this applies equally to nutrient recycling, as discussed in section 4.5). One grower also commented that low CO_2 costs won't change until a proper carbon trading system is in place.

The final word could be from one large scale VF operator who would not consider using waste CO_2 since its variable quality is incompatible with the closely controlled environment required by his consumers in the pharmaceutical and cosmetic sectors.

4.5 Waste Nutrients

Sources of nutrients in urban waste streams and the importance of recycling them is mentioned in section 1. No evidence of this in CEA was found and most interviewees reported similar reasons for not pursuing it, the lack of an economic driver and the risk to operations.

Nutrient consumption is low and nutrients are cheap. One operator stated nutrient costs for his 5,000m^2 VF farm was only £4,000 p.a, another commented that produce like hydroponic lettuce are very low in nutrients anyway, referring to them as “green water”. Additionally, organic certification, which could be a driver, is not available for hydroponics.

Organic nutrients increase complexity and risk of failure whilst bringing few benefits, other than the sustainability narrative, which is currently not a selling point, refer section 4.4 above. Interviewees mentioned risks like bacteria growth and pipe blockages caused by residues. A key driver of CEA is biosecurity and low bacteria count and adding organic nutrients is incompatible with this. One operator mentioned the penalties imposed by supermarkets if their crop failed the supermarket’s hygiene standards.

Some interviewees suggested it would, in fact, reduce yields. The quality of organically sourced nutrients from composts, or AD digestates can be unreliable, varying with feedstocks and season, making it a challenge to match the nutrient profile with the crop’s requirements.

Others also mentioned the possible contamination of urban waste streams, by pharmaceuticals, salt, etc whilst making biological connections between waste and food, especially human waste, is a contamination risk and public perceptions may not be favourable, although it may be that processing via an AD solves this problem. In Bristol, nutrients are recovered from sewage sludge and food waste via AD and sold to open field farmers, refer section 5.0.

To avoid these problems, several interviewees believed that converting these waste streams to energy in WtE plant would be more practical. Although nutrient recovery would then be less easy, at least the problem of safe waste disposal is solved in a more sustainable manner than incineration or to landfill.

Some interviewees mentioned that the VF industry is still more focused on achieving viable business models but may later turn to looking at sustainability issues and use of organic nutrients from waste streams. Many believed that use of organic nutrients in hydroponics is possible or could be possible, subject to further research regarding the problems of variability and sterilisation.

4.6 Water Capture/Recycling

As mentioned in section 3.2, ground based glasshouses tend to collect and utilise the rainwater from their own sites, a VF tech provider reported it has developed a system to capture and utilise rainwater and a large scale VF farm confirmed that they are already doing this. Presumably there is a certain scale of development where RWH is financially attractive because the consensus amongst smaller farm operators was that it is not a priority, since, as with waste CO_2 and nutrient streams, there is no economic motivation to do it, since water is not a big cost driver, plus that it adds further complexity and risk.

One interviewee discussed the higher quality of rainwater collection, with town water quality being variable, depending on rainfall levels and often contaminated with pharmaceuticals, oestrogen, fluorides, etc, but he also noted the expense to install and operate a rainwater system and the added complexity of having to flush through the system after dry periods to remove accumulated dirt.

4.7 Integrated Rooftop Greenhouses (iRTG)

Only three examples of iRTGs were discovered, one built and since demolished, one designed but not constructed and one still at concept stage.

The idea had at least 3 keen proponents amongst those interviewed, although conversely, a number felt strongly that the idea was not practical. The majority view was that iRTGs are a good idea but there are many barriers, chiefly the practical difficulties of installation, the cost and the problem of how to monetise the benefits, especially on mixed occupancy buildings.

Roofs may not be the flat, open, easily developed area that one might initially assume. They are often filled with plant and equipment and have poor access. Vertical transfer of inputs and outputs and personnel could be challenging, requiring access openings to roof level, service lifts, hoists and pumping systems. IRTGs will also often suffer from shading, especially during the low azimuth winter season, as was experienced by the Hackney IRTG and one interviewee felt that the same challenges as face VF, high labour requirements for sowing, harvesting and packaging, would be more difficult to automate efficiently in an IRTG. Roofs may also not be designed to take additional loads, requiring additional structural support costs, whilst high wind loads on roofs also need to be considered. Development may also run into permit difficulties. The Hackney IRTG apparently took 5 years to gain approval, although this was in a heritage area. Conversely the Ilford Market is part financed by the local authorities and approval was not difficult.

Creating an iRTG on a building roof is a multi-participant process and achieving common agreement can be difficult, especially considering the difficulties in resolving who pays for it and how the benefits provided by the integration are monetised in order to incentivise its development. Secondary issues involve who takes responsibility for its operation, for example during weekends and holidays, say if located on a school.

Whilst integrated heating and ventilation systems may offset the building's heating costs it may not achieve close control of indoor temperatures, such that either flexible attitudes or alternative heating systems may be needed.

The ability of iRTGs to achieve energy saving benefits has been the subject of much academic literature, (Mugford,2020) and was also reported at the Hackney IRTG, but there is no recognition of iRTGs in green building certification schemes. This was raised by one interviewee with BREEAM (Building Research Establishment Environmental Assessment

Method), who apparently responded that the benefits need to be verified first before they could consider it.

An interesting point raised by the Hackney IRTG owner is that the IRTG becomes a “fantastic’ rooftop resource, for habitation rather than crops, especially with current high London property prices.

However, it is hoped that a supermarket will before too long adopt the iRTG concept proposed by one interviewee and prove its feasibility. Meanwhile there may be more interest in community type IRTGs, driven by social benefits such as improved mental health, educational benefits and enhanced sense of community, (Pons et al., 2015, Sanjuan-Delmás et al., 2018) which could justify granting of government financial support, as has more commonly occurred in the USA, as with The Plant in Chicago (Al-Kodmany, 2018) and as is happening at the Ilford project.

4.8 Insects

4.8.1 Nutrients

Insect farming in the UK is a growing sector, especially of the black soldier fly (BSF), used in fish food and for indoor pets, who , as advised by one insect farmer, typically have less exposure to sunlight and thus poor calcium uptake, and therefore benefit from the BSF larvae’s high calcium levels. Whilst not all insects can grow on organic waste, interviewees all advised that it was possible with BSF, but all quoted the same challenge of finding reliable consistent waste nutrient sources. Lifecycles can double in length with poor quality feed and insects often tend to cannibalism if feed is lacking.

One operator was currently using fruit waste from a supermarket chain supplier which he blends with brewery byproducts, although this lacks protein so he is searching for some animal waste to supplement this. He had previously used food waste from supermarkets and found many problems, including daily variations in quality, inappropriate consistency, being often too sloppy due to too many bananas whilst BSF need a more aerated food stock, too much packaging, which was labour intensive to remove, occasional random items, like staples or keys, which could damage his shredder and poorly separated animal ingredients. He therefore prefers to use more easily managed wastes and is now looking at waste streams from food processors and packers, which may be more consistent.

An interesting point he mentioned is that supermarket food waste is generally collected and transported back to central locations, probably close to their main food distribution centres, which could allow an efficient circularity, where the same trucks delivering food can then bring back the waste, to be used in CEA located next to the distribution centres.

The challenge of using municipal food waste is the regulatory barriers which prevent use of post-consumer waste and the difficulties of separating animal byproducts.

4.8.2 Heating

Interviewees advised that temperature in insect farms must be controlled, typically to around 30°C and that heat is also needed to dry the frass (insect waste) and process any dried product. Colocation to use waste heat streams to heat the farm was attractive but those interviewed also mentioned the barriers to colocation. Insect farms tend to be unwelcome neighbours due to concerns over escapees, although one interviewee mentioned they had been offered a site next to an AD run on farm waste.

4.9 Colocation with Breweries / Distilleries

Colocation with breweries and distilleries, could in theory allow a number of synergies including use of the waste CO_2, use of digestate created by processing the brewery/distillery's organic liquid wastes in ADs and use of waste heat from the CEA's LEDs. However, no such integrated system was found and this may not be justifiable, economically.

5.0 Bristol

Bristol has an active group of public and private organisations working to promote sustainable change in the city. Some of these are summarised in Table 5.

Table 5: Summary of key organisations active in Bristol in the sustainability field and key publications relevant to this research.

Organisation	**Details**	**Key Documents**
Joy Carey	Food System Consultant	Who Feeds Bristol (Carey, 2011)
Bristol Food Policy Council (BFPC)	Established in 2011 to improve Bristol's food system, as a result of recommendations in Who Feeds Bristol (Carey, 2011).	Good Food Plan for Bristol, with the support of the BCC, (Bristol Food Policy Council, 2013) Good Food Action Plan 2015–18, (Bristol Food Policy Council, 2016)
Bristol Green Capital Partnership (BGCP)	Established by the BCC in 2007 to support and promote sustainability	Our Future. A Vision for an Environmentally Sustainable Bristol, (Bristol Green Capital Partnership, 2019).
Bristol One City	Launched by the mayor in 2019, to develop a roadmap to achieve sustainability by 2050.	One City Plan 2020, (Bristol One City, 2020b)
One City Environmental Sustainability Board	To oversee environmental aspects of the One City Plan	Bristol One City Climate Strategy, (Bristol One City, 2020a).

Organisation	Details	Key Documents
Energy Service Bristol	Part of BCC, helping Bristol to become carbon neutral by 2030.	City Leap Prospectus, (Energy Service Bristol, 2018)
Bristol Food Network (BFN)	Established in 2008 to drive collaboration and idea sharing. Helping to coordinate Bristol's bid for Gold Sustainable Food City by 2020.	
Bristol Food Producers (BFP)	Established in 2015 to help scale up local food production.	
Bristol Waste	Collect Bristol's solid waste, transporting it to Avonmouth and elsewhere	
GENeco,	Part of Wessex Water. Geneco convert Bristol's domestic food waste and sewage sludge via AD into biogas for supply into the city's gas grid and digestate for use on outdoor farms.	
Centre for Sustainable Energy (CSE)	Private sector energy consultants	Bristol Net Zero By 2030: The Evidence Base, prepared for the BCC, (Centre for Sustainable Energy, Ricardo & Eunomia 2019).
WASTE FEW ULL	Bristol is also currently one of 4 Urban Living Labs (ULL) involved in the WASTE FEW ULL project, designed to map and reduce waste in the urban food-energy-water (FEW) nexus.	

Bristol has also set several sustainability goals for itself, as listed in Table 6.

Table 6. Bristol's sustainability goals

Sustainability Goal	**Reference**
Achieve a healthy sustainably sourced resilient food system,	Bristol Food Policy Council, 2013
Become carbon neutral and climate resilient by 2030	Bristol Green Capital Partnership, 2019; Bristol One City, 2020b
Create a resource efficient circular economy by 2050, with zero waste	Bristol Green Capital Partnership, 2019

A review of relevant documents from these organisations and discussions with stakeholders revealed that there is a strong drive to maximise urban agriculture and to achieve efficient circular economies in resource use to help achieve these goals.

From a review of the policy statements (Bristol Food Policy Council, 2016) and as advised in a personal email from BFP, the drive to increase UA in Bristol is more focused on soil based and community led farms, driven by a desire to regenerate soils and to achieve social and mental health benefits and perhaps also a perception by some stakeholders that soilless grown food is less nutritious. The BCC has stated that the need to integrate food growing into residential developments will be considered when assessing planning applications, although requirements are vague and are, mirroring the above opinion, expressed in terms of the social benefits of green spaces, rather than the desire to maximise food production, (Bristol City Council, 2014). The One City Environmental Sustainability Board's Bristol One City Climate Strategy (Bristol One City, 2020a) does however specifically mention the need to support roof farming and VF, although, as advised by one board member, this strategy is still very much at the concept stage. This should be encouraged though, since a properly integrated and resilient city food system must include diversity and the year round food production capability of CEA can complement soil based UA.

There is also a strong drive to achieve efficient circular economies in resource use and a circular economy plan for Bristol will apparently be published by 2021 (Bristol Green Capital Partnership, 2019). However, from a review of the various policy statements, (Bristol Green Capital Partnership, 2019Bristol One City, 2020a, Centre for Sustainable Energy, Ricardo & Eunomia 2019, Energy Service Bristol, 2018) and as per discussions with stakeholders, the focus for resource use seems to be on meeting the BCC's commitment to carbon neutrality by 2030, by selecting the most carbon efficient uses of the gas generated from the city's waste. Hence Bristol's domestic food waste is collected and delivered to Avonmouth by Bristol Waste, where it, together with sewage sludge from Wessex Water's STP is processed by Geneco in ADs. The gas from the ADs is stripped of CO_2 and fed into the local gas grid for cooking and heating buildings, or as fuel for buses. Meanwhile residual waste, unfit for recycling, is processed at 2 other WtE plants which generate electricity to the national grid.

There is considerable waste heat from these processes. There is also heat embodied in the incoming sewage stream, especially from the stream diverted to assist cooling of the nearby Seawater gas power station, but it is understood from the interviews that this heat is not yet being utilised. A consultant in the waste sector believed the waste heat available would be in the order of 3 digits of MW and recovery could possibly be an investable proposition, although he and others did note the challenges, including that government subsidies may be necessary to make it commercially feasible and colocation, which would probably be necessary to make it feasible, would be difficult since the neighbouring land, owned by Wessex Water, is reserved for possible future expansion of their STP facilities. Wessex Water also noted that they weren't aware of any overtures from the private sector to use this waste heat, although expectations are that more focus will be placed on this in the future. One option currently under consideration, as mentioned by the Geneco interviewee, and as stated in the City Leap Prospectus, is to feed the heat into district heating schemes, (Energy Service Bristol, 2018).

There is also a circularity in nutrient use. Geneco advised that the digestate from their ADs is sold to local open field farmers as a substitute for inorganic fertilisers. However, there is no reuse of the CO_2, which could amount to almost 45% of the gas produced by an AD. Geneco advised the technology to commercially capture this CO_2 is not yet available.

There was no mention of circularities between these urban waste streams and CEA though, although the option to build glasshouses at Avonmouth, to utilise the recycled waste nutrients, water and heat from the facilities, was a recommendation back in 2011 by Joy Carey in Who Feeds Bristol, (Carey, 2011). The waste CO_2 could potentially also supply these.

6.0 Conclusions

The aim of this paper was to find out whether synergies between urban waste streams and CEA in the UK are being adopted, and if not, what are the barriers and challenges to achieving them and then look at the status at the city level, in Bristol, regarding resource management to facilitate these synergies.

Most interest was found to be in utilising cheap waste energy derived from urban waste streams or waste heat from urban facilities and buildings, although critically, TCEA is unlikely to require heat inputs. Despite the interest, only one example was identified, of tomato glasshouses utilising heat from sewage treatment plants, although there is also one VF project, still confidential at time of writing, proposing colocation with a data centre to use its reject heat.

There was currently little interest amongst CEA stakeholders in using CO_2 and nutrients from urban context waste streams due to its risks and the lack of economic drivers. Production of highly standardised, clean produce in high tech VFs depends on tightly controlled environments and consistent quality of inputs whilst resources derived from urban waste may be inconsistent or of low quality, thus bringing extra complexity and risk into the operation. This seems to be especially unwelcome at this stage in the sector's development, where many operators, especially the smaller ones, are more focused on trying to create viable, scaleable business models in the face of high start-up and operating costs, rather than on considering environmental sustainability angles. Adoption of these synergies also requires economic drivers which are currently lacking due to the often high investment costs needed to achieve them and the low value of the resource. Moreover, the market is more focused on the message of consistent, clean, nutritious, local produce than on sustainability.

More research is needed into organic nutrient use, to overcome problems with variability and contamination and how to add into hydroponic farming systems. Issues with public perceptions regarding mixing urban waste streams with food production must also be a consideration.

Larger scale operations seem to be adopting rainwater harvesting as routine, although this research has not investigated what scale of roof and water demand is needed to make this a worthwhile investment.

The possibility that adoption of these synergies may increase in the future was mentioned by a number of the interviewees, who expect future growth and stabilisation of the industry, driven by greater profitability due to technology improvements, plus by possible rising food prices following Brexit and the resultant disruptions in food supply chains, as foreseen by several analysts, (Barons & Aspinall, 2020), and a possible post Covid 19 drive for more reliable food supply chains in the UK where currently around 75% of the UK's fresh fruit and vegetables is imported, (Savills, 2019). These trends could help the sector become more profitable and stable, such that the focus may shift more towards sustainability issues and resource use circularities.

No operational examples of rooftop greenhouses integrated into the building's metabolism were found. The concept in principle is promising though and could have a viable future, however, there are many practical challenges, as described in section 4.7.

A review of relevant literature released by Bristol organisations and discussions with Bristol based stakeholders revealed a drive in Bristol to maximise UA and to achieve efficient circular economies in resource use, especially of solid waste streams. However, little interest was found in promoting CEA and developing synergies between buildings, urban waste streams and CEA. The current focus seems to be on soil based UA, motivated by an interest in soil regeneration and the social benefits of community led agriculture.

The focus for achieving resource circularities is driven by the city's commitment to achieve carbon neutrality by 2030. Food waste and residual waste is diverted from landfill to ADs or gasification plants with the intention to then use the resultant gas in the most carbon efficient manner, currently mainly to supply electricity into the national grid and gas into the local gas grid, whilst nutrients from the ADs are recycled to outdoor farmers for soil amendments.

Bristol's focus on reducing carbon emissions raises the question of whether this is in fact the correct approach when considering resource use. A future line of research could involve evaluating circular economy options using a more holistic framework than just the simple carbon calculation, to include considerations of the wider social, environmental and health benefit potentials of other uses of the resources, including for UA and CEA, the focus of this paper. This might help justify the development of scaled up CEA in Avonmouth, as discussed in section 5 above. It might also justify more localised waste collection and decentralised small scale AD and WtE plants in cities which could supply colocated local small scale CEAs with power, CO_2 and nutrients, enabling greater circularities, more local food production and more system resilience. This feeds into the debate over the resilience benefits of diversity against the efficiency of big centralised systems that has been brought to prominence by the supply chain vulnerabilities exposed by Covid 19, and which should also be part of the analysis.

Developing circular strategies for waste management should of course not divert focus from the more important requirement of reducing waste at source, and possible conflicts of interest between these two positions must be managed.

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