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A desk-based study to determine an optimised greenhouse design bolstering local food production within the UK

Kieran Joshua Lim [1] and Xiaofeng Zheng [1]*

[1] *Department of Architecture and Built Environment, University of Nottingham, Nottingham, NG7 2RD, United Kingdom*

ABSTRACT

This paper identifies the shortcomings in the current agricultural sector that contribute to a lowered domestic food production – specifically the high cost of operating horticultural practices – as a critical issue affecting the United Kingdom's food security and sustainability, thus leading to a heavy reliance on vegetable imports. A case study into an allotment in Beeston, Nottingham, provided insights into challenges faced by non-commercial food producers, and thus advocates for an enhancement of local communities' ability to bolster their own fresh vegetable consumption through the use of small greenhouses. Simulations were run through IES Virtual Environment on a conventional single-span greenhouse as well as one which incorporated various design modifications and management systems – explored for their ability to optimise greenhouse efficiency. The resulting discrepancy in output variables demonstrated an overall improvement in performance between the traditional and modified greenhouses, with the proposed solution increasing heat retention by 30.4% and decreasing heating costs per square meter by 9.5% over the course of a year. Since simulated data is not always accurate to real-world conditions, further study may include building a physical structure to properly analyse the performance increase and feasibility of such a design. Nonetheless, the research proves that the optimisation of greenhouse design is an opportunity for the industry to reduce its reliance on imports as well as promote sustainable practice.

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1. INTRODUCTION

The current situation in the UK reveals an overreliance on fresh vegetable imports as only 58% of consumed vegetables are produced domestically, as well as the issue of a disproportionate imports to exports ratio for fresh vegetables, with 2.7 billion tons of vegetables are imported per year, as compared to 85 million exported (Department for Environment, Food & Rural Affairs, 2022a); underscoring a broader concern regarding the nation's food security and sustainability. Unfortunately, in the UK there is a lack of design standardisations within the agricultural sector that can be seen in other countries such as the Netherlands, Japan and the United States, which may further contribute to lowered food production. This is compounded by a lax enforcement of

* Corresponding author. Email address: Xiaofeng.Zheng@nottingham.ac.uk (Xiaofeng Zheng)

nutrient management plans and other operational inefficiencies – with half of agricultural holdings in the country not having an appropriate nutrient management plan, as well as a third of holdings not having a system in place for fertiliser management either (Department for Environment, Food & Rural Affairs, 2022a), whether due to ignorance, poor planning or more likely, costs. The current financial impact these holdings have on the UK economy is £767 million spent annually on operational costs for horticultural practices (Department for Environment, Food & Rural Affairs, 2022b); thus, the need to find viable solutions becomes even more pronounced when taking into consideration the environmental impacts of long-distance transportation for food.

Addressing this issue necessitates a way to empower local communities to enhance their food production capabilities, subsequently mitigating the dependence on imported produce that could feasibly be cultivated domestically. Specifically, this dissertation explores the use of small greenhouses in non-commercial settings, reflecting an acknowledgement of greenhouses leading to greater yields for staple vegetables in the UK diet as well as a common way in which farming can be optimised.

A greenhouse is a specialised structure designed for plant cultivation under a controlled microclimate, typically constructed with transparent materials like glass or plastic. The greenhouse facilitates an absorption of solar energy in its surfaces, trapping heat and thus leading to an increase in internal air temperature, creating an optimal environment for extended growing seasons and greater yields. Despite their undeniable benefits however, greenhouses are notable consumers of energy, distinguishing them from other facets of the agricultural industry, with typical costs of £5.1/m^2 and £67.5/m^2 for electricity and heating respectively for protected intensive crops (Carbon Trust, 2006). As such, the reduction of energy consumption in greenhouses is a fundamental objective for sustainable food production.

This paper endeavours to address the domestic food production issue by reducing the operational cost of running greenhouses, making them more feasible in local communities and other non-commercial practices, thus lessening the reliance on fresh vegetable imports. A design solution will then be determined to optimise the efficiency of said greenhouses, whether through changes to the design fabric or to management systems within the structure.

To gain a comprehensive understanding of the challenges faced by non-commercial food producers, a brief case study will also be conducted at a community allotment in Beeston, Nottingham. When focusing on this specific locale, the investigation aims to delve into not only the motivations for using the allotment, but also the challenges faced by local communities, with particular regard given to the physical obstacles preventing an improvement of production in current practice.

The case study explored the dynamics of a local community in the form of an allotment in Beeston, where local volunteers and a non-profit association sustain its operation. The allotment is approximately 7.5 acres in size, divided into 120 plots of 250 m^2 each. Notably, the greenhouses within this setup are largely self-constructed and of simple designs as seen in the following Figures 1 and 2.

Figure 1. Current greenhouse setup at Beeston Allotment 1 (Even-span Gable).

Figure 2. Current greenhouse setup at Beeston Allotment 2 (Gothic Arch).

The volunteers themselves cited various motivations for using the allotment, such as:

- Having inherited the land from previous generations
- Allowing users to stay connected with the community
- Being more self-sufficient
- Contribute to sustainable living
- Providing an escape from daily life
- Provide fresh produce and improve the biodiversity of the locality

Despite these positive aspects of communal farming activities, the allotment struggles with an inability to be self-sufficient, stemming from suboptimal utilisation of its growing facilities. The challenges are exacerbated by financial constraints, as the local government is unable to allocate enough funding for the expansion or enhancement of facilities. Compounding these financial issues is the combination of a limited volunteer network and a reliance on an internal barter system amongst the volunteers themselves, rather than engaging with local farmers' markets.

The main focal point however, is the physical aspect of the problems faced by the allotment. Volunteers have highlighted issues related to a lack of greenhouse activity during the more extreme seasons, thereby affecting their functionality. During the summer months, the greenhouse environment becomes unconducive to plant growth due to inadequate ventilation and limitations in maintaining an optimal temperature. This discomfort from excessive heat not only affects plant development, but also the thermal comfort of the volunteers working within.

Similarly, as winter sets in, the drop in temperatures reduces the chances of successful cultivation. The absence of proper heating systems also limits the greenhouse's ability to provide a stable and warm environment, affecting both thermal comfort for human use and suitable conditions for plant growth.

The insights gained from this case study may also extend beyond the Beeston allotment, as they can be extrapolated to be applicable to other small communities across the UK. Thus, this suggests that in order to enhance the functionality of greenhouses across the country, we must be able to address the issues brought forward by the volunteers at this allotment, primarily in the form of a comprehensive strategy involving the implementation of changes to the greenhouse envelope, or the addition of ventilation systems suitable for warmer seasons as well as effective heating solutions for the colder months. This approach would seek to optimise the greenhouse environment, ensuring a consistent and favourable climate year-round, thereby fostering more resilient agricultural practices within local communities.

2. ENERGY EFFICIENT MEASURES IN THE GREENHOUSE DEVELOPMENT

Central to this proposal is a comprehensive understanding of design modifications and their impact on the traditional greenhouse structure, aiming to identify and leverage opportunities for improving energy efficiency as well as overall functionality. Emphasising a prioritisation of minimising costs, this literature review will investigate how passive systems, designed to harness natural elements such as sunlight and ventilation, can be strategically implemented to create a more sustainable and economical greenhouse.

Beyond architectural considerations, the dissertation will also delve into other aspects of greenhouse management, optimising environment conditions such as light quality and quantity, temperature, humidity, ventilation, CO_2 concentrations and soil quality so as to increase plant growth and yields (Van der Zanden, 2008, Liliane and Charles, 2020). This includes an exploration into alternative heat management systems, seeking solutions that optimise temperature control without a significant energy footprint, as well as the implementation of intelligent control systems within the greenhouse environment to further enhance resource utilisation.

2.1. CHANGES TO STRUCTURE

2.1.1. GREENHOUSE SHAPE

A 1976 study found that a gothic arch shape required 15-25% less heating than an even-span gable or a Quonset shape (Chandra, 1976), however it should be noted that here the gothic arch shape was modified such that there are no vertical components as seen in other studies. This led to a decrease in overall surface area in contact with the ambient, affecting the heat balance equations used in his calculations. Similarly, in 2002, a similar study used the same modified gothic arch shape to show a 2.6 - 4.2% increase in effectiveness compared to even-span gable and Quonset shaped greenhouses in Delhi (Gupta and Chandra, 2002).

As seen in Figure 3, a study on the thermal performance of five standard greenhouse shapes under the weather conditions of New Delhi, India was conducted (Singh and Tiwari, 2010). The findings revealed that the uneven-span gable roof greenhouse exhibited the highest solar radiation absorption, attributed to the larger surface area of the uneven-span design, making it more effective in receiving solar radiation. Thus, the uneven-span gable roof greenhouse demonstrated the least requirement for additional heating to maintain optimal indoor temperatures. Similarly, in a theoretical investigation, another study explored solar radiation availability in greenhouse structures across three different climate conditions (10°N, 31°N, and 50°N) in India. The results indicated that the uneven-span design necessitated the least supplementary heating across all latitudes, generally mirroring the study mentioned previously in New Delhi, however with less comparability as latitude increased (Sethi, 2009).

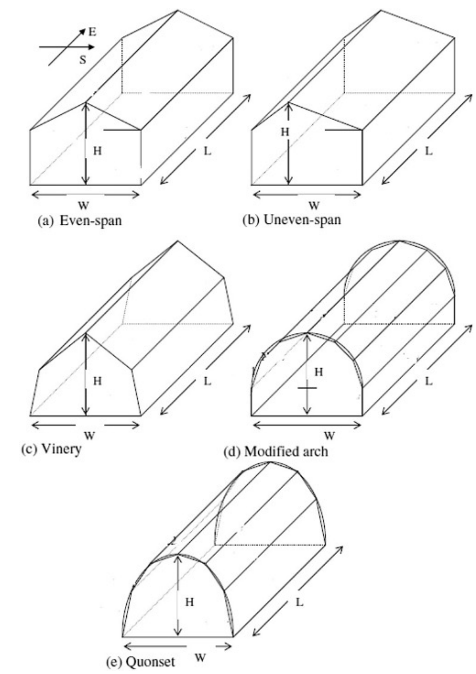

Figure 3. Comparison of standard Greenhouse shapes (Singh and Tiwari, 2010).

Conversely, Ahamed et al. compared the performance of five types of greenhouse designs in Saskatoon, Canada and found that the Quonset shape required 7.6% less annual heating to maintain suitable temperatures for plant growth in a single span construction (Ahamed, Guo and Tanino, 2018a). In the same year, the group concluded that local climate was the most important factor in determining an ideal greenhouse shape, as the heat gain from solar radiation per unit area of cover may be less than the rate of heat loss through the fabric

(Ahamed, Guo and Tanino, 2018b).

Table 1. Comparison of studies to determine a suitable greenhouse shape for the UK, along with their latitude, evaluation criteria and findings.

Description of Study	Evaluation Criteria	Ideal Shape
3 Shapes in Winnipeg (49N) (Chandra, 1976)	Solar Gain	Gothic Arch
3 Shapes in New Delhi (28N) (Gupta and Chandra, 2002)	Heating Requirement	Gothic Arch
5 Shapes in Bayburt (40N) (Çakır and Şahin, 2015)	Solar Gain	Gothic Arch
5 Shapes in New Delhi (28N) (Singh and Tiwari, 2010)	Heating Requirement	Uneven Span
5 Shapes in Saskatoon (52N) (Ahamed, Guo and Tanino, 2018a)	Heating Requirement	Quonset

Table 1 above provides an extensive overview of various studies that were systematically compared (Ahamed, Guo and Tanino, 2019), which has helped to determine an optimal greenhouse shape suitable for the United Kingdom in this dissertation. The key criteria considered in this comparison included latitude, the primary objective of the study, and the key findings derived from each investigation. Figure 4 depicts a comparable latitude range between the UK and the vast majority of Canada, spanning between 50°N to 60°N.

Figure 4. Graphical depiction of comparable latitudes between the UK and Canada.

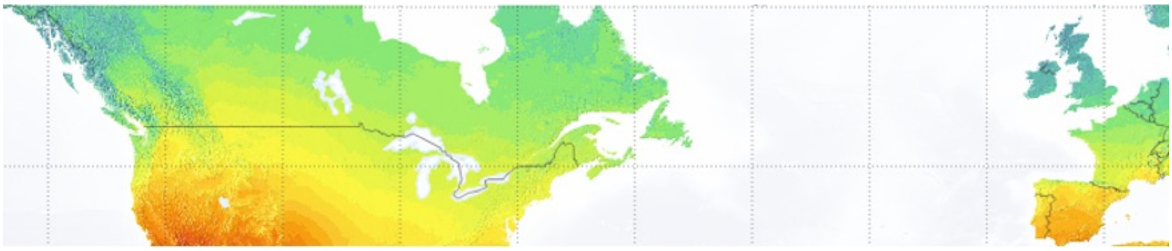

Figure 5. Global Horizontal Irradiance levels in the UK and Canada.

Research has identified the Quonset shape as the most suitable for a single-span greenhouse in the UK, drawn from the studies acknowledging the Quonset shape's efficiency in Canada. Despite the climatic distinctions between Canada and the UK, primarily due to the Gulf Stream effect, there is a similarity in the amount of solar radiation gained from sun exposure – as seen in Figure 5, measuring Global Horizontal Irradiance (GHI). Though not entirely identical in value, this shared characteristic is pivotal in affirming the applicability of the Quonset shape to the UK.

2.1.2. HIGH THERMAL MASS NORTH WALL

To determine an optimised greenhouse design, it is imperative to extend beyond the selection of an ideal shape and address the critical aspect of temperature regulation within the structure. As such it is possible to incorporate a north wall with high thermal mass, specifically for the storage and controlled release of solar energy accumulated during daylight hours. A review conducted by Santamouris looked at various heat-storing north walls, revealing a 30-50% reduction in heating demand in greenhouses featuring a solid north wall compared to counterparts without this feature (Santamouris, 1993). In the subsequent year, Santamouris et al. reported an 82% saving in heating energy within a 30 m^2 greenhouse with a 600mm thick insulated north wall, particularly when external temperatures ranged from 3-5°C, and the internal air temperature maintained an approximate 10°C above ambient temperatures (Santamouris, Argiriou and Vallindras, 1994).

A study done by Gupta and Tiwari compared the thermal performance of brick, concrete, and mud north walls. The findings indicated that while a concrete north wall exhibited the highest energy storage capacity, a mud north wall remained a viable option for colder climates where daytime heating may be required (Gupta and Tiwari, 2005). The energy exchange dynamics between the room air and the wall, denoted as qwall-gh, are noted in Figures 6 and 7 below. It is observed that the maximum energy exchange displayed minimal variance between concrete and mud north walls, despite the substantial differences in overall energy gain.

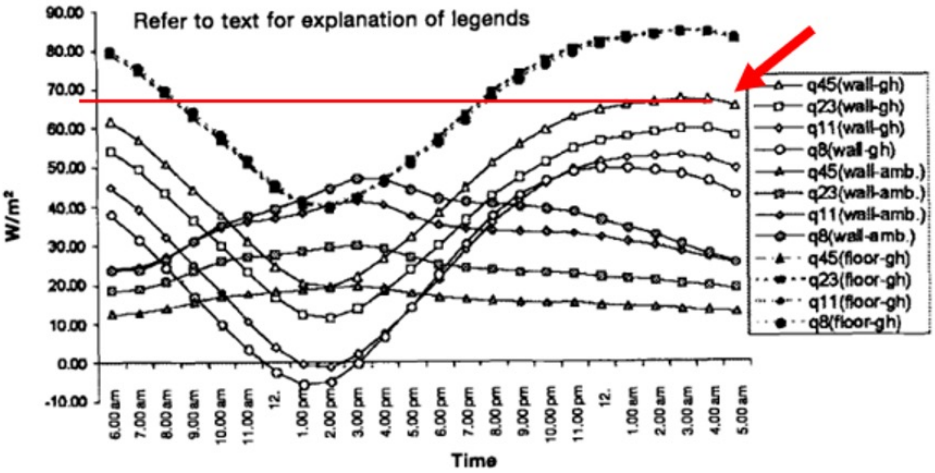

Figure 6. Energy transfer over 24 hours in a greenhouse with a mud north wall (Gupta and Tiwari, 2005).

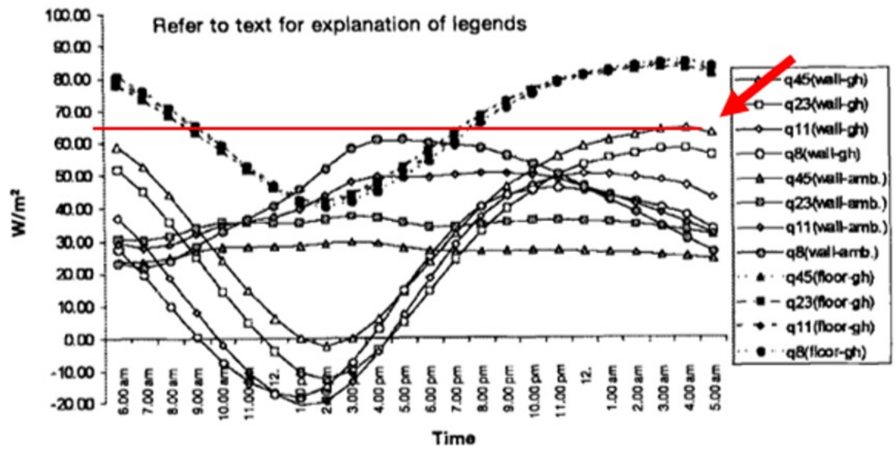

Figure 7. Energy transfer over 24 hours in a greenhouse with a concrete north wall (Gupta and Tiwari, 2005).

Delving into the mass producibility aspect of the proposed optimised greenhouse, rammed earth emerges as a potential material for the north wall due to its low carbon footprint and cost-effectiveness. Despite potential concerns regarding water damage in the British climate, a waterproofing additive known as Plasticure, developed by Australian company Tech-Dry, presents a promising solution. Findings revealed the effectiveness of cement-stabilised rammed earth with a Plasticure additive, exhibiting lower microscopic pore network connectivity, thus resulting in reduced water absorption without compromising wall durability, as absorption rate and moisture content were significantly lower in this combination than other arrangements tested (Meek, Beckett and Elchalakani, 2020), illustrated in Figure 8. These observations affirm the viability of rammed earth, especially when augmented with the waterproofing additive, as a pragmatic choice for the proposed greenhouse's north wall.

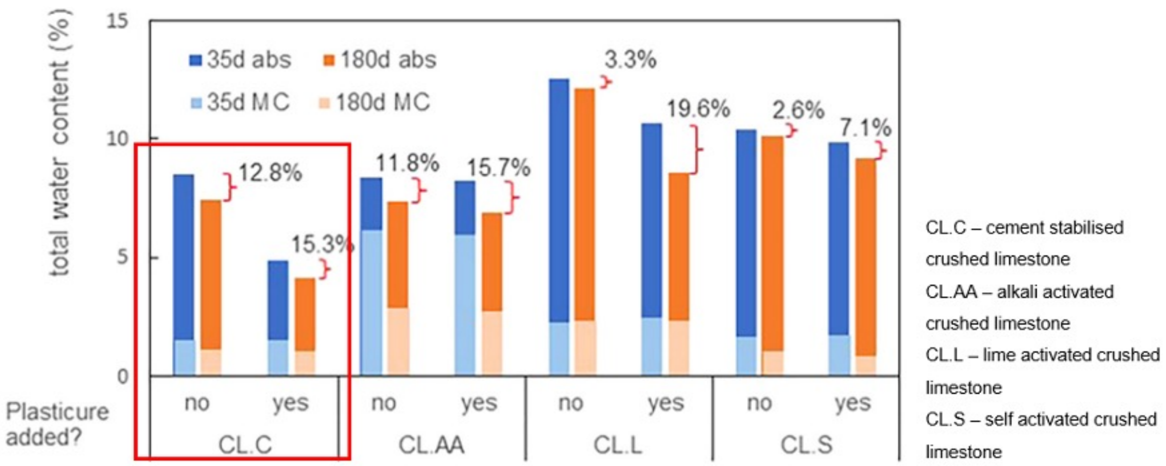

Figure 8. Absorption rate and moisture content in various Rammed Earth configurations (Meek, Beckett and Elchalakani, 2020).

2.1.3. THERMAL SCREENS

Thermal screens, commonly referred to as night curtains, have been employed to mitigate the loss of thermal radiation during cold nights, especially during the winter months. These thermal screens have proven to be effective in reducing radiation losses by a substantial margin of approximately 40-70% (Andersson, 2010).

A study by Sethi and Sharma highlights the impact of thermal curtains on energy conservation in greenhouses, indicating potential energy savings up to 60%, with the possibility of reaching an impressive 90% when coupled with passive heating systems, such as a thermal mass storage (Sethi and Sharma, 2008). This value is of course heavily idealised and assumes minimal if not no heat loss from other sources; at this juncture there has been no research to quantitatively prove this claim.

Various types of curtains, including aluminised screens, polyester screens, polypropylene monofilament, and vinyl screens, have been explored to address improvements in greenhouse heating, with studies (Andersson, 2010, Teitel et al., 1999, Zhang, 1996) having delved into the energy-saving potential of these options. The collective findings suggest that energy savings can vary from 20% to 60%, depending heavily on factors such as location and the specific type of thermal screen employed.

Sethi et al. demonstrated the effectiveness of aluminised polyester sheets as night screens in a greenhouse in India, resulting in a 3-4°C increase in indoor temperature compared to an unshielded greenhouse (Sethi et al., 2003). Aluminised thermal screens stand out due to their high reflectivity, surpassing other materials like polyester, polypropylene, and polystyrene; however, it must be noted that these aluminised screens increase cost significantly as well – contradicting with the mass-producibility ethos of this research. In contrast, other studies focused on screens made of PE and polyester materials, and demonstrated energy-saving effectiveness of 16% and 19.8% respectively (Abak et al., 1994, Öztürk and Bascetincelik, 2003).

2.1.4. DIFFUSIVE FILMS

In regions characterised by higher solar radiation, direct sunlight can induce leaf burning in greenhouse crops on summer days. To mitigate this issue, plastic films have been used to enhance the proportion of diffuse radiation within the greenhouse, also known as turbidity.

Augmenting turbidity not only enhances light uniformity but also contributes to increased yields in Mediterranean countries (Castilla and Hernandez, 2007). For instance, Magán et al. observed cucumber yields of 20.5 kg/m^2 in a greenhouse with a plastic diffusing film (52.8% diffuse light), compared to 16.7 kg/m^2 in a glasshouse (34.6% diffuse light) (Magán et al., 2011).

The positive effects of a diffusive light cover extend to Western European countries such as the Netherlands as well, with Hemming et al. conducting a comparison between diffusive glass and clear glass, concluding that under a diffusive glass, the crops were able to receive more light and therefore resulted in a higher assimilation rate (Hemming et al., 2008). Similarly, a study by Dueck et al. demonstrated a 9.2% increase in cucumber productivity in the Netherlands through the use of a highly diffusive cover with a turbidity of 70%, despite transmission values reducing by 3% (Dueck, 2009). Though the optimal turbidity percentage for achieving maximum yield is yet to be determined in south and central European environments, the potential for increased productivity when utilising diffusive films is higher in regions where the direct radiation percentage is greater than the 30% found in this study.

It should be noted that this is a common arrangement even in low-tech setups such as the case in the Beeston Allotment, with many volunteers shielding their greenhouses with thin cloth to protect from direct sunlight – one user in particular allowing hops to grow over her structure during the spring so as to cover the roof in vines before the summer months.

2.1.5. VENT ARRANGEMENT

Outside of direct changes to the greenhouse envelope, a lack of ventilation leads to a decreased thermal comfort within the space and therefore decreased use of the greenhouse especially during the summer months, as explored earlier in the Beeston allotment case study, as well as increased humidity levels, which adversely impacts crop yield and quality (Hand, 1988) by promoting the growth of fungi such as Botrytis cinerea which may lead to fungal diseases. Additionally, it can induce leaf necrosis and calcium deficiencies, leading to stunted growth and delayed plant development (Mortensen, 2000).

Regardless of location, natural ventilation remains the most straightforward, cost-effective, and practical method for users to modify the microclimate in greenhouses. This ventilation method influences the greenhouse's energy balance and gas concentrations, addressing water vapour, CO_2, and the removal of potentially harmful gases from various sources. Efficient natural ventilation goes beyond achieving a high number of air exchanges; it also requires effective mixing of internal and external air for uniform temperature distribution and improved air movement within the canopy to enhance heat and mass exchange with the plants (Bailey, 2000).

Typically, greenhouses feature roof openings aligned longitudinally along the main span axis, often situated near the ridge or gutter in a multi-span greenhouse; commonly employing either roll-up or pivoting-door closure systems. However, Bournet and Boulard found that smaller greenhouses benefit from higher ventilation efficiency when equipped with sidewall vents instead of relying solely on roof vents (Bournet and Boulard, 2010).

Similar findings emerge from research done by Kacira et al., advocating for a dual approach utilising both sidewall and roof vents. The study demonstrates a ventilation effectiveness of approximately 20 times greater than that achieved by solely employing roof vents. In Figure 9, Graph A represents this combined strategy which significantly outperforms Graph B in the same figure in terms of air exchanges per minute (Kacira et al., 2004).

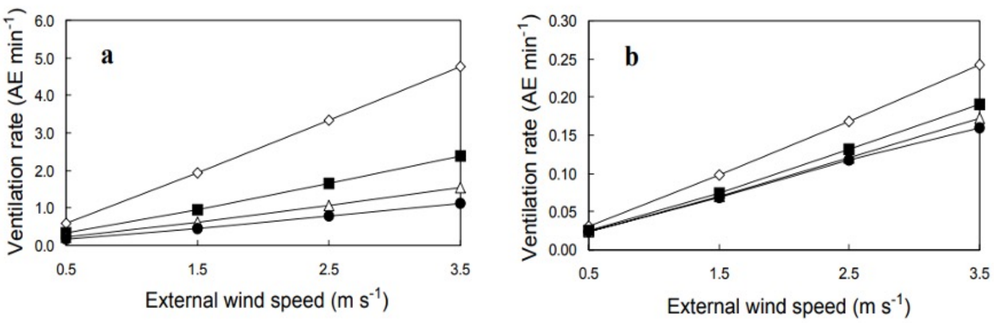

Figure 9. The effect of windward side external wind speed on greenhouse ventilation rates, where graph A represents both sidewall and roof vents and graph B only roof vents (Kacira et al., 2004).

2.1.6. ROOF DEFLECTORS

While effective ventilation is important to maintain the greenhouse microclimate, a common challenge arises when the circulation of air tends to concentrate at the upper regions of the greenhouse, particularly when only roof vents are utilised, as air often follows the path of least resistance within a structure. To counteract this limitation, the implementation of a deflector becomes necessary to redirect the airflow downward.

Nielsen's study demonstrated the positive impact of a vertical deflector positioned below a double roof vent in a single span greenhouse. This resulted in a notable reduction of average temperatures within the greenhouse by 2.1°C and an enhancement of air exchange rates along the greenhouse floor by approximately 50% (Nielsen, 2002). It must be taken into consideration however, that this study was conducted in a controlled environment without crops, implying unhindered airflow along the floor which may be potentially damaging in the presence of vegetation.

One solution involves elevating the crops, allowing the air to pass underneath them, or reducing the deflector's length to facilitate the homogenisation of the stream with the internal air above the crops.

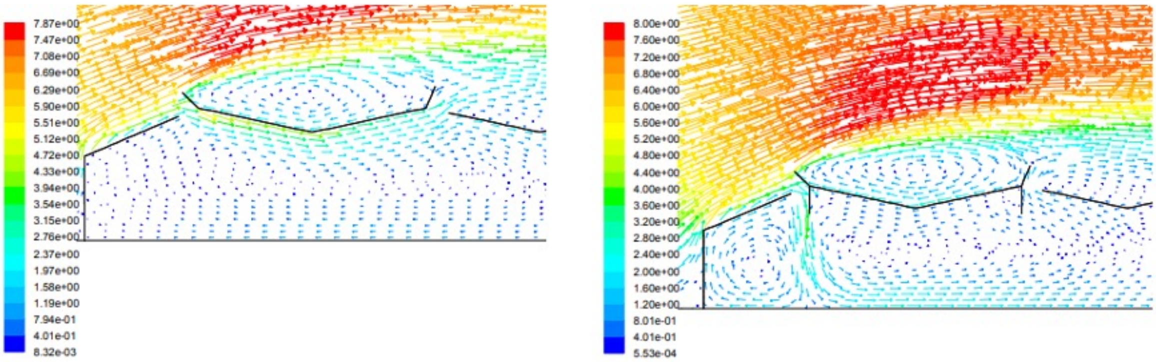

Figure 10. Simulations done to show the effect of a vertical deflector on air flow (Baeza et al., 2006).

In Figure 10, CFD simulations conducted by Baeza depict the findings mentioned above, with the deflected airflow redirected downwards, as compared to the typical case of air circulating at the top of the conventional greenhouse (Baeza et al., 2006).

2.1.7. REFLECTIVE SURFACES

In greenhouse design, the incorporation of reflective surfaces helps to enhance productivity by homogenising distribution to parts of the greenhouse that may not necessarily receive as much sunlight as others. The ensuing increase in light transmissivity not only fosters a more favourable environment for plant growth but also contributes to resource efficiency. The following studies were done with reflective surfaces installed on a vertical north wall, an inclined north wall reflector as well as a reflective film installed horizontally on the ground:

A study by Thomas to investigate the impact of specularly-reflecting back walls on the transmissivity of greenhouses was conducted in 1978 which utilised computer simulations written in FORTRAN IV and was implemented on an IBM 370/165. This study also assumed a reflectance of 90%, comparable to aluminium foil, and incorporated weather data from the Kew Meteorological Office. The findings of the study revealed that the use of specularly-reflecting back walls could significantly increase the amount of light reaching the greenhouse floor, as seen in Table 2. Specifically, greenhouses with a transparent north wall exhibited an average transmissivity of 76% over the 11th to the 15th of six months between the years of 1959 and 1960, whereas greenhouses with a reflective wall demonstrated an average transmissivity of 91% during the same period examined (Thomas, 1978).

Table 2. Transmissivities in a greenhouse with and without a reflecting back wall (Thomas, 1978).

	11-15 Oct. 1959	**11-15 Dec. 1959**	**11-15 Feb. 1960**	**11-15 April 1960**	**11-15 June 1960**	**11-15 Aug. 1960**
Transparent back wall						
Direct	0.81	-	0.76	0.76	0.75	0.77
Difuse	0.78	0.73	0.75	0.76	0.75	0.76
Total	0.79	0.73	0.76	0.76	0.75	0.77
Reflecting back wall						
Direct	1.30	-	1.29	1.10	0.88	1.04
Difuse	0.91	0.79	0.86	0.86	0.75	0.82
Total	1.02	0.79	1.01	0.93	0.80	0.90

For a single-roofed (slope back to front) greenhouse with vertical walls. Length = 10.0 m, width 3.5 m, height to eaves =1.5 m, height to ridge = 3.2 m. Front wall faces due south. A dash indicates that there was no direct radiation during the period examined.

Several studies have discovered that incorporating reflective materials on the north wall of a greenhouse at an angle is a cost-effective method to reliably enhance light intensity (Li, Kurata and Takakura, 1998, Cai, Nu and Zhao, 1994, Kong and Meng, 2004). However, another study devised a formula to further determine optimised dimensions and an angle of incidence at any given time in greenhouses in China between latitudes of 32°N and 42°N (Kong et al., 2008). Table 3 below shows the results of these calculations.

Table 3. Calculated results for optimising the installing height and rotation angle of reflective board (Thomas, 1978).

Time (hh:mm)		**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**
Calculated parameters	α (°)	6.5	14.9	21.4	25.6	26.8	25.0	20.4	13.5	4.9
	θ (°)	-52.2	-41.1	-28.3	-13.9	1.4	16.6	30.7	43.1	54.1
Calculated results	Hmax (m)	0.23	0.41	0.49	0.52	0.51	0.47	0.40	0.29	0.1
	βmax (°)	11.6	13.3	13.9	14.2	14.5	15.1	15.9	16.6	16.7
	β’max (°)	18.6	16.6	15.2	14.4	14.5	15.4	17.2	19.7	22.7

Note: β'_{max} is the optimal rotation angle when the installation height of reflective board was 0.5 m throughout the whole day.

Ideally, such adjustments would be mechanically controlled through a sensor and algorithm, however due to the high economic cost of operating such a set-up in the proposed greenhouse design discussed in this dissertation, this aspect will be overlooked.

Boo et al. conducted a study measuring sugar concentration in aubergines at various developmental stages with different types of polyethylene mulch placed horizontally below the plants. Their findings revealed that across all four mulches, sucrose, glucose, and fructose concentrations increased during fruit development. However, the reflective and white mulches induced consistently higher activities of the sucrose synthase enzyme compared to the black and transparent mulches (Boo et al., 2010), as depicted in Figure 11.

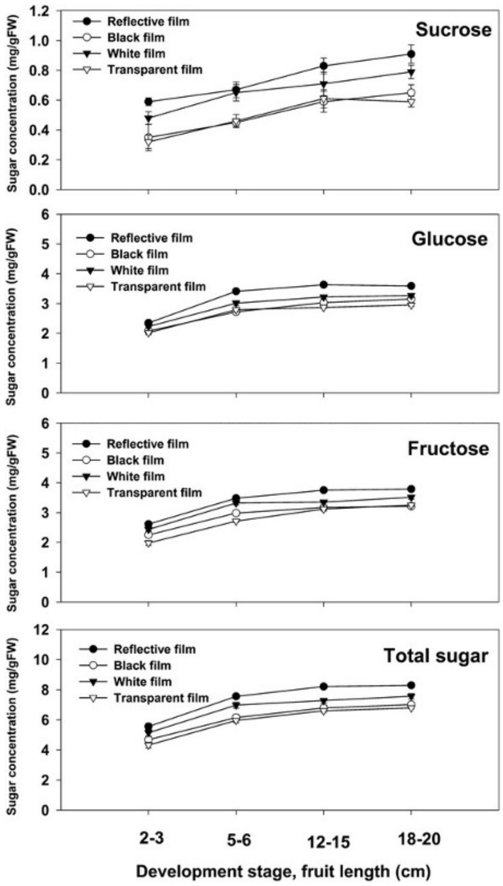

Figure 11. Changes in contents of sucrose, glucose, and fructose in eggplant fruits during fruit growth with different polyethylene mulches (Boo et al., 2010).

2.2. ALTERNATIVE HEAT MANAGEMENT SOLUTIONS

2.2.1. ANAEROBIC DIGESTION

In the anaerobic digestion process, organic materials such as food waste and wastewater sludge, are collected and introduced into a sealed digester. Within this controlled environment, microorganisms, particularly anaerobic bacteria, break down complex organic compounds through a series of stages. The residual material left after digestion, known as digestate, is a nutrient-rich substance which has significant agricultural value as a fertiliser (Nkoa, 2013).

This microbial activity also results in the production of biogas, composed mainly of methane and carbon dioxide. This biogas is then captured and has the potential to be harnessed as an energy source. However, potential risks exist due to the flammability and explosiveness of methane in biogas, as well as the release of toxic gases like hydrogen sulphide that may lead to health issues such as paralysis, asthma, respiratory issues, contagion and death (Macor and Benato, 2020a, Macor and Benato, 2020b, Benato and Macor, 2021) should the biogas not be treated properly.

In light of this, it is unrealistic to expect a small community to have the facilities to process biogas safely, thus while anaerobic digestion has the potential to be a sustainable source of energy and fertiliser, at this juncture the risks outweigh the benefits of anaerobic digestion for a greenhouse at the scale put forward by this dissertation.

2.2.2. COMPOST HEAT RECOVERY

Compost heat recovery involves harnessing the heat generated during the aerobic decomposition of organic materials by microorganisms like bacteria and fungi in a compost pile. A basic use of this is as a heat generator for small spaces, though air quality becomes an issue without proper ventilation. In 2021, a study found that a compost heat recovery system (CHRS) may be used to cover more than 50% of the energy demand in a small building such that there is an increase in internal gains (Malesani et al., 2021).

Within the Beeston Allotment explored in the case study for this dissertation, it was found that the community has an agreement with one of the local stables to supply horse manure to use as fertiliser. A few studies as seen in Table 4 below were explored to calculate the energy output of a CHRS should the community decide to implement this in their greenhouses, with specific reference to research done in 2019 (Bajko, Fišer and Jícha, 2019). This particular study was chosen due to its similarity to what materials are available to the greenhouses at the Beeston Allotment.

Table 4. Thermal power output data collection from different prototypes of Compost Heat Recovery Systems (CHRSs).

Composted Material	Average Power	Energy Recovered		Monitoring Time	Volume
	kWm^{-3}	MJm^{-3}	$MJkg_{biomass}^{-1}$	days	m^3
Horse manure, sawdust, woodchips (48)	0.14	302	0.8	25	0.9
Horse manure, sawdust, fresh grass (47)	0.1	311	0.8	36	6.7
Cow manure, fresh grass, sawdust (49)	0.2	225	0.6	13	2.8

A rough estimate of the energy produced per year by such a set up can thus be calculated using Eq.(1):

$$Q_T = P_{Avg} \times V \times 24hr \times 365days \quad (1)$$

Where, P_{Avg} is the average power output density by volume produced by the compost, (kW/m^3);
V is the size of the compost in volume, (m^3);

$$Q_T = 0.1kWm^{-3} \times 6.7m^3 \times 24hr \times 365days = 5869.2\ kWh\ per\ year \quad (2)$$

Thus, given the space constraints and energy produced, a CHRS may be an option to supplement part of the heating load required for the proposed new greenhouse, especially during the colder months to ensure the space is operable throughout the year.

2.2.3. GROUND SOURCE HEAT PUMP

A ground source heat pump (GSHP) is a sustainable heating and cooling system that harnesses the stable temperature of the ground's subsurface to regulate indoor climate; relying on soil below the surface having a more consistent temperature throughout the year, remaining cooler than surface temperatures in summer and vice-versa in winter. The GSHP system consists of a loop of pipes buried in the ground or submerged in a stagnant water source; a heat pump then circulates a heat-exchange fluid through this loop, absorbing heat from the ground in winter and rejecting heat to the ground in summer, thereby regulating the temperature of the space.

Despite many studies (Fine et al., 2018, You and Yang, 2020) having confirmed that a GSHP allows for high efficiency as a passive form of heating, it is also important to note that continuous use leads to serious thermal imbalance in the soil, which leads to the deterioration of energy efficiency and thus increased costs over time (Yang et al., 2022). Similarly, since the system requires an extensive area or a deep borehole that goes down approximately 10-15 meters, initial costs of implementation also make it unfavourable for the average user; as such a GSHP system is unsuitable for the proposed design (Harjunowibowo, Omer and Riffat, 2021).

2.2.4. HEAT EXCHANGE PIPE (EARTH-AIR HEAT EXCHANGERS)

Earth-Air Heat Exchanger (EAHE) systems are constructed as buried pipes or networks underground at a specific depth to circulate air within a space. The temperature difference between the air and soil is used to substitute cooled or heated air in a space, aiding in both summer cooling and winter heating. Typically situated at depths of 1–6 meters, the system leverages the relatively constant soil temperature at this depth, which is lower than summer temperatures and higher than ambient temperatures in winter. Due to its reliance on only a small fan for circulation, an EAHE proves to be an economical and practical solution for heat management.

In 1986 a study was conducted on a greenhouse's performance which utilised an early EAHE, comprised of 20 aluminium pipes, each with a length of 15 meters, a diameter of 0.2 meters, and a thickness of 0.2 millimetres. These pipes were installed at a depth of two meters within a greenhouse with a floor area of 150 square meters. To regulate the greenhouse air temperature, the air was circulated through the pipe system whenever it fell outside of an arbitrarily set 12-28°C boundary. Consequently, this approach led to a minimum mean night air temperature of 8.1°C inside the greenhouse. In comparison, the outside minimum mean air temperature was -0.8°C during the same period (Mavroyanopoulos and Kyritsis, 1986).

Similarly, a study done in the Shaanxi region of China (34°N) tested the effects of an EAHE on the winter and summer temperatures of a greenhouse, and found that the EAHEs can increase night temperatures in winter by 1.41°C and decrease day temperatures in summer by 1.87°C, as well as effectively reduce indoor air temperature fluctuation. The setup had the following parameters as seen in Figure 12 below: "EAHE in the experimental greenhouse was buried in the north trough inside the greenhouse at a depth of 2.5m and consisted of 26.9 m long PVC pipe with 0.16 m inner diameter, including a 4.5 m long inlet pipe, a 19.1 m horizontal heat exchanger pipe and a 3.3 m outlet pipe" (Xiao et al., 2023).

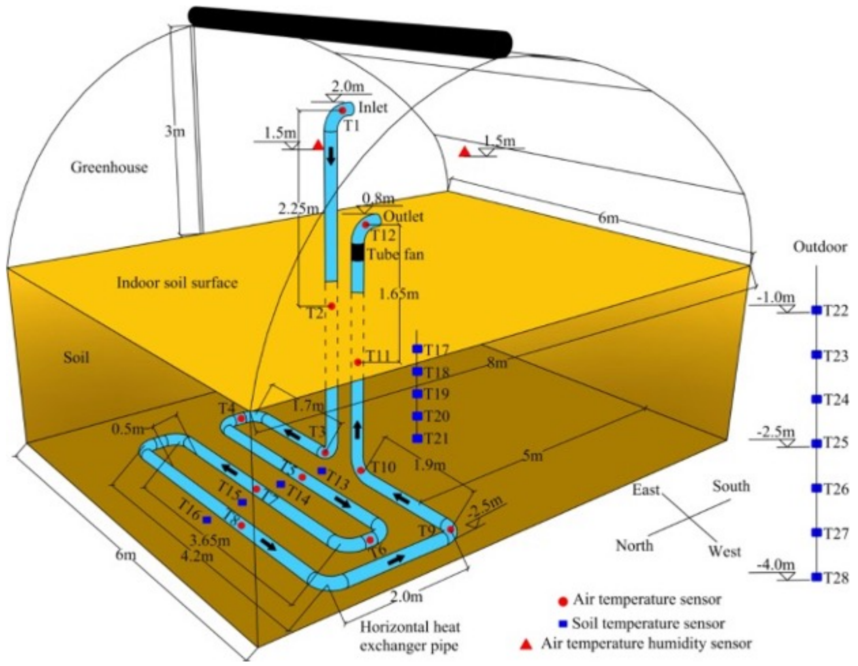

Figure 12. Schematic of the EAHE setup (Xiao et al., 2023).

Given the comparability in scale of the latter study and the design put forward by this dissertation, it is more reliable to refer to temperature differences found by Xiao et al. rather than Mavroyanopoulos et al. for the purposes of sizing an EAHE system. That being said however, the cost of implementation for a greenhouse of this size outweighs the negligible change to internal air temperatures.

2.3. INTELLIGENT CONTROL SYSTEMS

Greenhouse management is a multifaceted optimisation challenge that impacts crop yield and the efficient utilisation of resources. To address this issue, Liu et al. proposed employing sensor stations to oversee the greenhouse environment (Liu et al., 2022). Similar studies have found that a monitoring system in greenhouses allow for better regulation and maintenance of the microclimate within, gathering a constant stream of data which thus optimises pesticide use and energy consumption as well as reducing the need for human intervention, thus further encouraging plant growth and maximising yield and quality (Gonda and Cugnasca, 2006, Liao et al., 2017, Xu, 2001, Wang et al., 2008).

Research indicates that the growth rate of tomatoes in an automated greenhouse utilising an Internet of Things (IoT) monitoring system is twice as fast (Siddiqui et al., 2017, Martinović and Simon, 2014), assuming environmental factors such as temperature and humidity are sustained at specific levels. Azaza et al. demonstrated that employing this system can reduce energy consumption by approximately 25% and water consumption by 33% (Azaza et al., 2016), a value reinforced by another study in the same year (Pitakphongmetha et al., 2016). Additionally, a monitoring system equipped with an intelligent decision module can effectively enhance decision-making capabilities and mitigate losses resulting from misjudgements (Mann, Harris and Harris, 2006). In general, automated control systems allow for better environmental control within the greenhouse so as to promote growth and monitor plant development, as well as to better manage fertiliser application/disease prevention measures.

Li et al. found that an intelligent monitoring system plays a crucial role in energy saving, emission reduction, yield increase and quality improvement of a greenhouse, when allowed direct control of the following parameters:

- Fertigation and acid dosing
- Irrigation
- Lighting
- Motors (ventilation control)
- Data Recording

The same paper also highlights a large issue in the industry at the moment, that is that most of the literature currently only introduces the environmental factor sensors or systems they use, rather than a quantitative study of their effect on plant growth (Li et al., 2021). In general, control systems are an important part of any setup, and oftentimes the cost of implementing a basic sensor and motor is low enough to justify for a greenhouse of any size.

3. METHODOLOGY

As explored previously, the UK's current reliance on imports of produce that could be grown domestically leads to increased consumer costs, forcing local communities to produce their own food so as to supplement consumption – however, more often than not the operation of such facilities is expensive and produces a low yield volume with traditional greenhouses.

In order to combat this, this paper therefore proposes a new design (henceforth known as the modified greenhouse) for mass-production, one that leverages on the modifications studied in the literature review, which were chosen for their proven effects on the greenhouse microclimate, as well as their feasibility to be implemented.

To quantify the differences between the traditional greenhouse and the modified greenhouse, simulations of both designs were created using IES Virtual Environment, as seen in Figures 13 and 14, and their analysed results compared. This software was selected for its range of integrated analysis tools and focus on performance optimisation, allowing for controlled conditions while still incorporating various variables such as airflow, heating/cooling loads and sun exposure; as well as its simulation reliability to quickly compile performance metrics and compare the resultant data in a presentable manner.

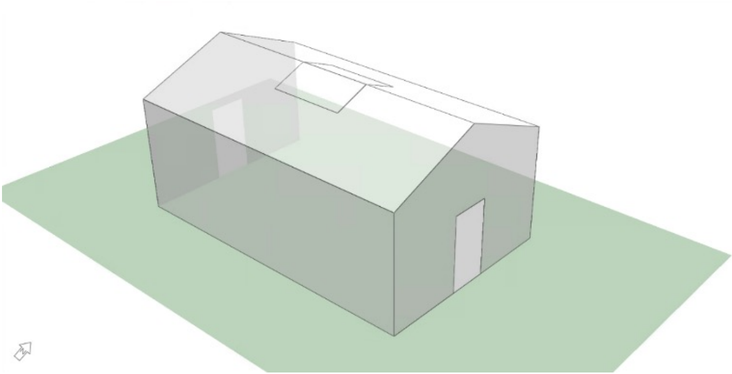

Figure 13. Traditional Greenhouse Design modelled in IES Virtual Environment.

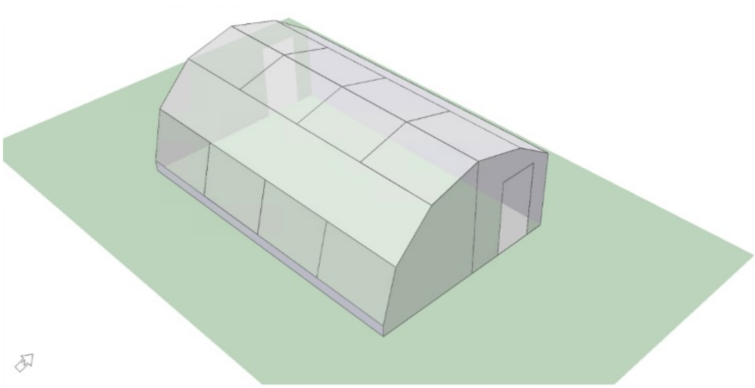

Figure 14. Modified Greenhouse Design modelled in IES Virtual Environment (Quonset simplified into a polygonal shape for vent placement).

The experiment was designed to test the overall effect of the combined modifications to the traditional greenhouse, thus certain construction properties remained constant across the two simulations.

The materiality within both simulations remained the same for all components apart from the earthen north wall in the modified greenhouse, for example the main external fabric of both greenhouses was taken to be a 10 mm thick polycarbonate supported by an aluminium frame, and the simulated ground material was set to 500 mm of cultivated sandy soil with 25% moisture content – chosen for its similarity to an average soil type within the UK.

The dimensions for both greenhouses were arbitrarily set at eight meters long and five meters wide; large enough to house various plant arrangements, but small enough to still fit in a backyard or as explored earlier in the Beeston case study, a plot within an allotment.

Although there is little literature on height requirements for freestanding greenhouses, Building Regulations 2010 states that planning permission from a local council is required should the overall height of the greenhouse exceed four meters, in the case of an even-span gable, or three meters for any other roof type (Gov.Uk, 2010). Thus, in the case of this comparison, the traditional greenhouse was taken to be a 4-meter tall even-span gable, and the modified greenhouse a 3-meter tall modified Quonset.

Table 5. Design changes explored in the literature review, and rationale behind their inclusion/exclusion in the modified greenhouse.

Design Change	Findings	Implemented	Rationale
Greenhouse Shape	Quonset		Low Heating requirement
High Thermal Mass North Wall	Rammed Earth Wall		30 – 50% Reduction in heating demand
Thermal Screens	Polyester Curtain		19.8% Energy-saving effectiveness
Diffusive Films	70% Turbidity		9.2% Increase in productivity
Vent Arrangement	Roof + Sidewall Vents		2000% Increase in air exchanges per minute
Roof Deflectors	Vertical Deflector		50% Increase in airflow rate
Reflective Surfaces	Horizontal films		Higher enzyme activity in plants/fruits
Anaerobic Digestion	Health risks		Toxic if not treated properly – facilities req
Compost Heat Recovery	Horse Manure		50% of Heating demand covered
Ground Source Heat Pump	High efficiency		Thermal imbalance, high installation costs
Heat Exchange Pipe	Low effect on temp		High installation cost for minimal change
Intelligent Control System	Necessary		Data collection and automated vent control

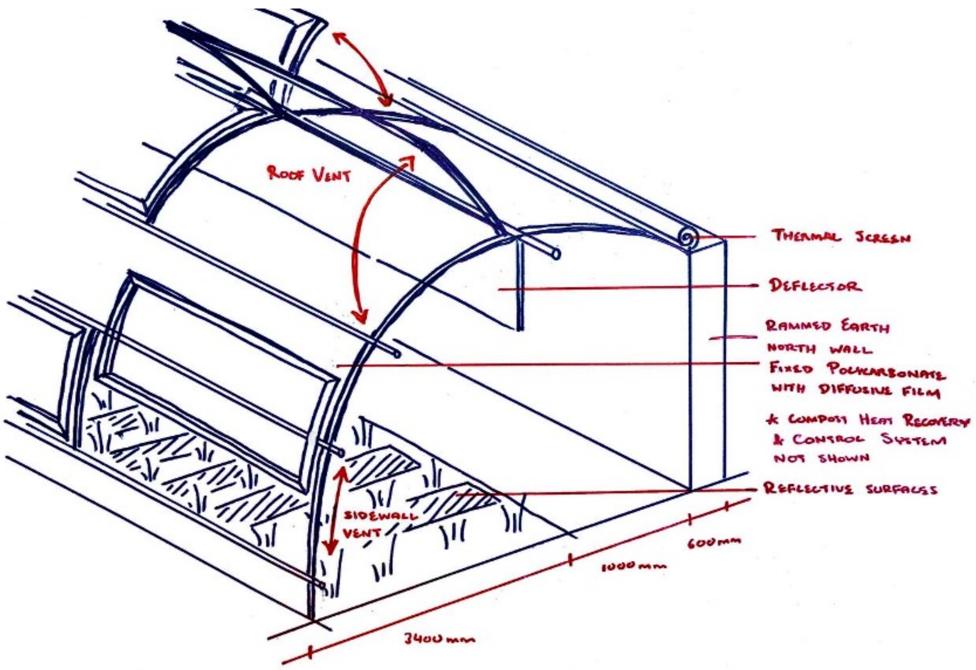

Figure 15. Proposed Design of The Modified Greenhouse According to the Literature Review.

The various design changes explored in chapter 3 were compiled and compared for implementation in the modified greenhouse. Table 5 highlights the changes and rationale behind inclusion in the final design – a brief sketch of which is seen in Figure 15.

It should be noted that a desk-bound study cannot always accurately simulate real conditions, however IES Virtual Environment remains the software of choice for exploring the differences between the traditional and modified greenhouse designs, due to its ability to compare relationships between variables reliably and with more accuracy than other methods of data analysis such as Autodesk Insight and other Building Information Modelling (BIM) software.

Both simulations were located in the Beeston Allotment of Nottingham, thus the Nottingham weather data found in the Virtual Environment default library was used for this research. Similarly, the occupancy profile was built around the typical times these volunteers would tend to the vegetables in their greenhouses; which was then used to calculate internal gains from people, where a CLO value of 0.5 and medium activity was assumed. Other internal gains and losses were taken to be constant between the two tests, with appliance gains remaining at zero and infiltration rates set at 0.75 ach^{-1} for both simulations, the only exception being the inclusion of a compost recovery heat system found in the modified greenhouse, which was set to output a constant power of 0.1 kWm^{-3}.

The simulations were then tested for the following variables:

- Air temperature
- Natural Ventilation (in the form of Macroflo External Ventilation)
- Room CO_2 Concentration
- Predicted Mean Vote
- Solar gain versus External Conduction Loss
- Total Energy Consumed

4. RESULTS AND DISCUSSION

In order to properly test for the modified greenhouse's effectiveness in reducing operational costs, it was important to assume that the space was heated to maintain an optimal plant growth temperature throughout the year, with the exception of the summer months where the space was instead cooled with natural ventilation. To achieve this, Total energy consumed was recorded as a separate dataset as well, with schedules used in both simulations to better demonstrate how the greenhouses may be run in practice – heating added if air temperatures within the space drop below 21°C between the months of September and April, and ventilation opened if air temperatures within the space exceeded 25°C at any time during the year.

To better understand the operational costs saved by converting to the modified greenhouse design, the recorded values for natural gas used over the year were then converted to a monetary amount based on current gas pricing – 7.29 p/kWh as of December 2023 (Knight, 2023). The difference in annual prices per square meter were therefore used as an indication of energy saved.

4.1. AIR TEMPERATURE

In Figures 16 and 17, it is evident that the air temperature within the greenhouses generally follows the same trend over the course of the year, with temperatures during the day stabilising between April and October. However, the air temperature within the traditional greenhouse tends to be higher than the air within the modified greenhouse – at noon on the hottest day of the simulation, the 29th of July, the external dry-bulb temperature read 27.10°C, with the maximum air temperature within the traditional greenhouse recorded at 32.33°C as compared to the maximum found in the modified greenhouse, which showed 27.91°C.

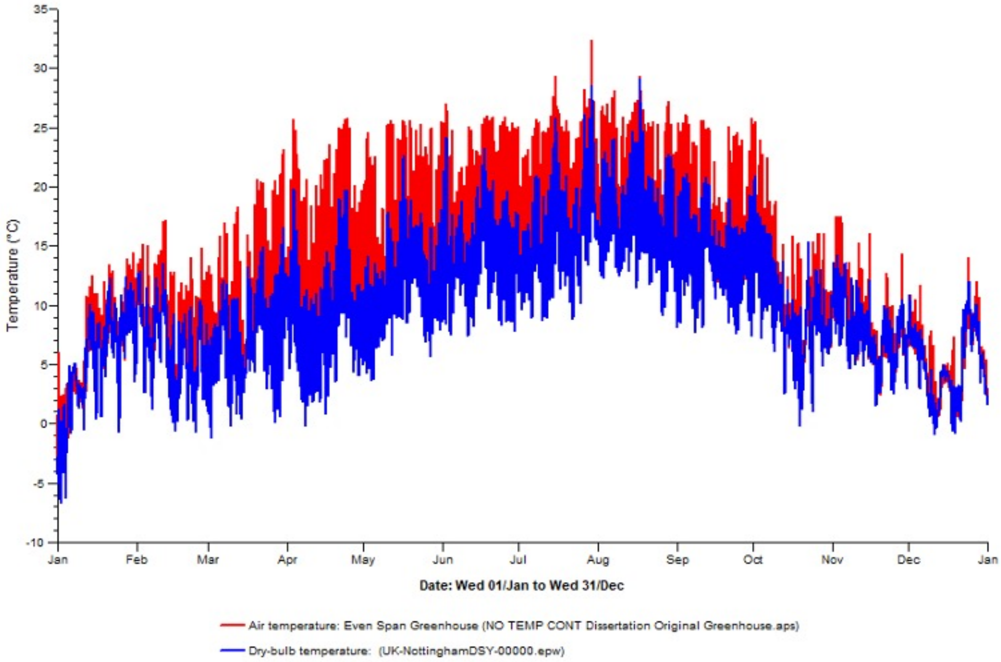

Figure 16. Internal Air Temperature (°C) versus External Dry-bulb Temperature (°C) in the Traditional Greenhouse design.

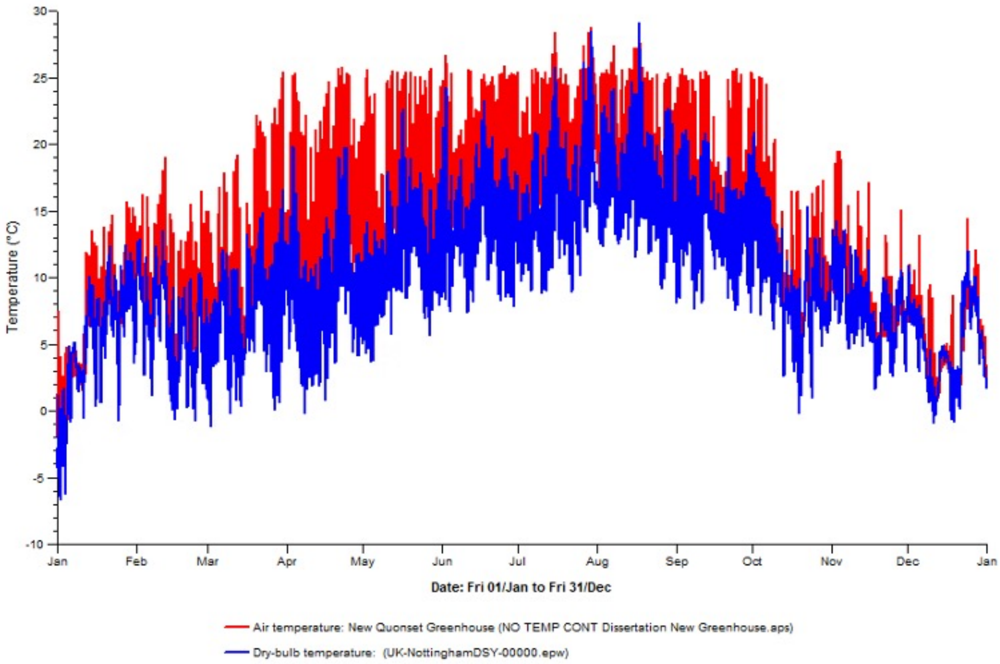

Figure 17. Internal Air Temperature (°C) versus External Dry-bulb Temperature (°C) in the Modified Greenhouse design.

Although not perfect conditions for stimulating plant growth, 27.91°C is still within the acceptable range for internal air temperatures as it is not high enough to induce severe water loss and wilting in vegetation. Conversely, the 32.33°C found in the traditional greenhouse proves to be too hot for both plant growth and human use, as observed in the Beeston Allotment case study.

As both simulations were set to open their vents when temperatures within exceeded 25°C, the difference in just over 4°C between designs was likely due to the implementation of sidewall vents to better manage the heat during the summer, as well as the increased number of total vents allowing for more airflow through the structure.

4.2. NATURAL VENTILATION (IN THE FORM OF MACROFLO EXTERNAL VENTILATION)

It should be noted that since the vents operate on a 25°C temperature threshold, the openings remained closed during the colder months to retain heat, hence the lack of data from October to March in both Figures 18 and 19.

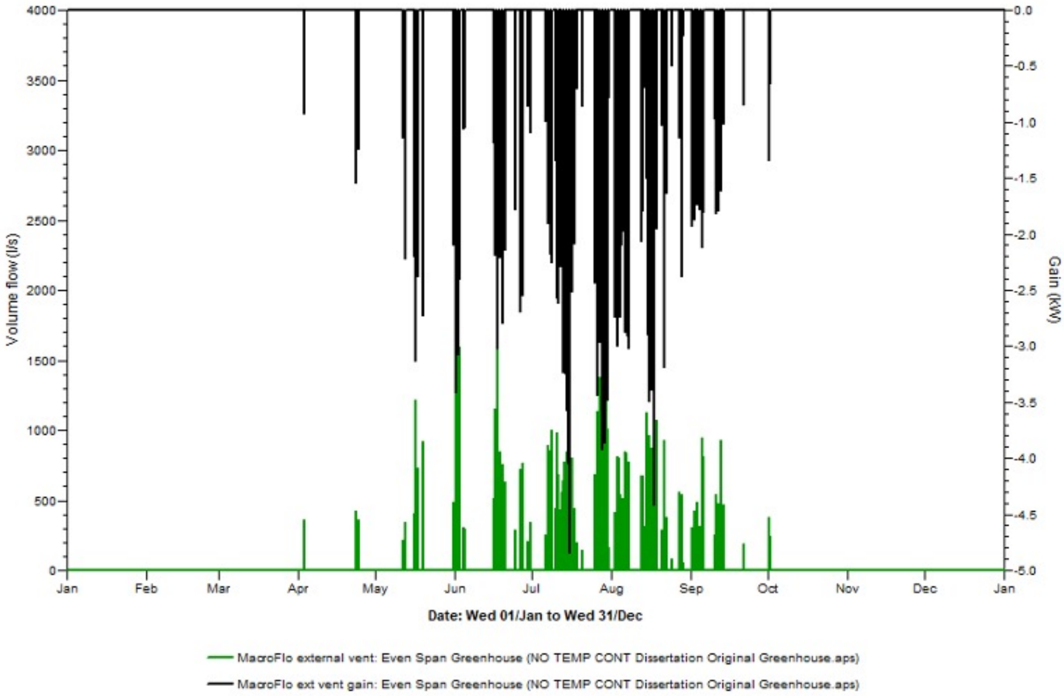

Figure 18. Natural Ventilation recorded in the form of Macroflo External Ventilation (l/s) against heat losses from said ventilation (kW) in the Traditional Greenhouse Design.

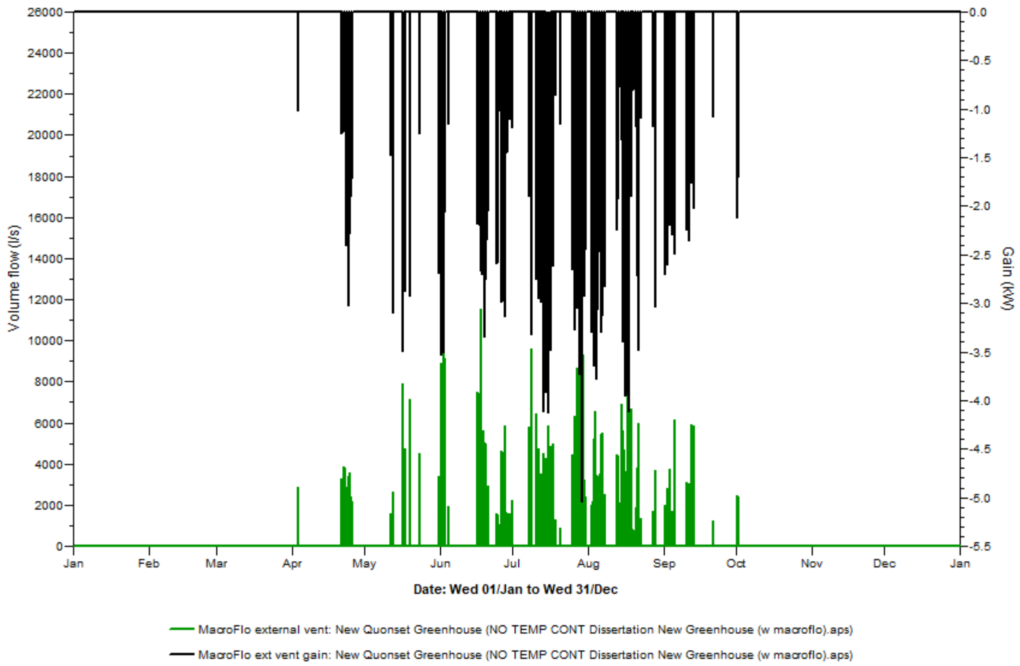

Figure 19. Natural Ventilation recorded in the form of Macroflo External Ventilation (l/s) against heat losses from said ventilation (kW) in the Traditional Greenhouse Design.

Nonetheless, the implementation of proper vent arrangement consequently increased the volume flow rate of air through the structure – the mean value of air flow was recorded as 28.18 l/s and 183.82 l/s for the traditional greenhouse design and the modified greenhouse design respectively, highlighting an approximate

600% increase. Different experimental conditions are likely the reason why this value is not as large as the significant 2000% improvement as seen in the experiment by Kacira et al. in 2004.

Interestingly, the heat losses from natural ventilation were 0.73 MW for the traditional design and 0.93 MW for the modified design, the difference here disproportionate to the volumetric air flow given the 600% increase across simulations. This is likely due to a base value of heat loss for having at least one vent to regulate heat – the additional roof vents providing diminishing returns for the modified greenhouse. Further study can be done to optimise the number of openings to therefore reduce production cost.

4.3. ROOM CARBON DIOXIDE CONCENTRATION

The concentration of carbon dioxide in both greenhouse designs remain relatively constant throughout the year, only diminishing during the summer months in conjunction with the opening of vents. In Figure 20, there is a general trend for the concentration to reach approximately 1050 ppm in the traditional greenhouse design, as compared to 1300 ppm in the modified greenhouse as seen in Figure 21. Though at first glance this may be attributed to a lower infiltration rate in the modified greenhouse, both structures were set to have an infiltration rate of 0.75 air changes per hour (ach^{-1}); instead, the increase in concentration is likely due to either the presence of a solid north wall reducing air gaps along the construction, or the presence of the compost heat recovery system. Since decomposition is an aerobic process, the microorganisms convert the organic material and oxygen into heat for the space and produce carbon dioxide as a byproduct.

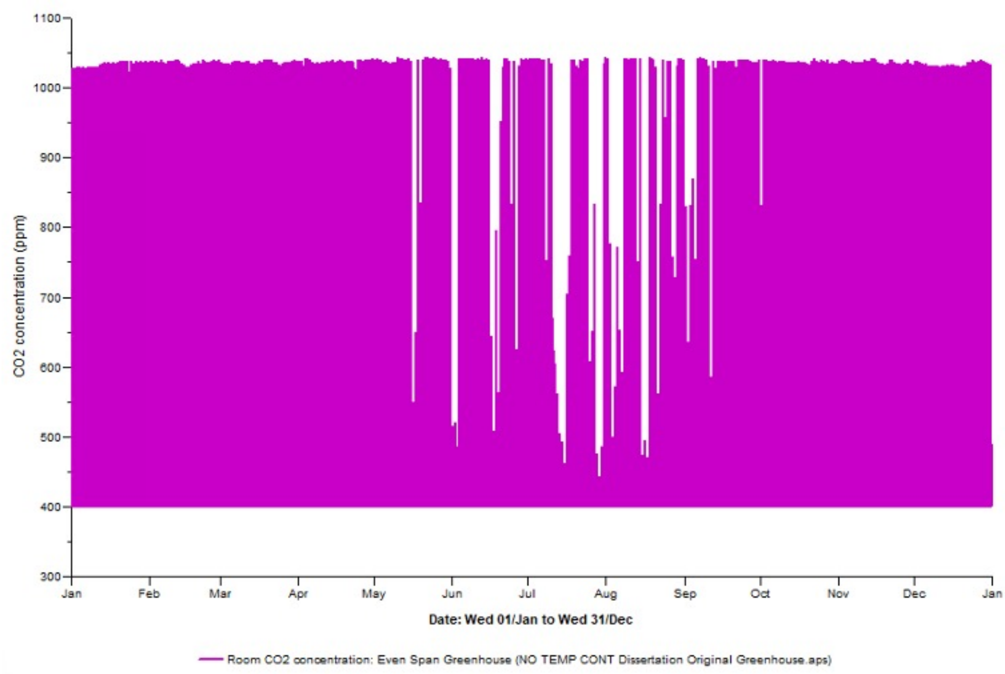

Figure 20. Room Carbon Dioxide Concentration in the Traditional Greenhouse (ppm).

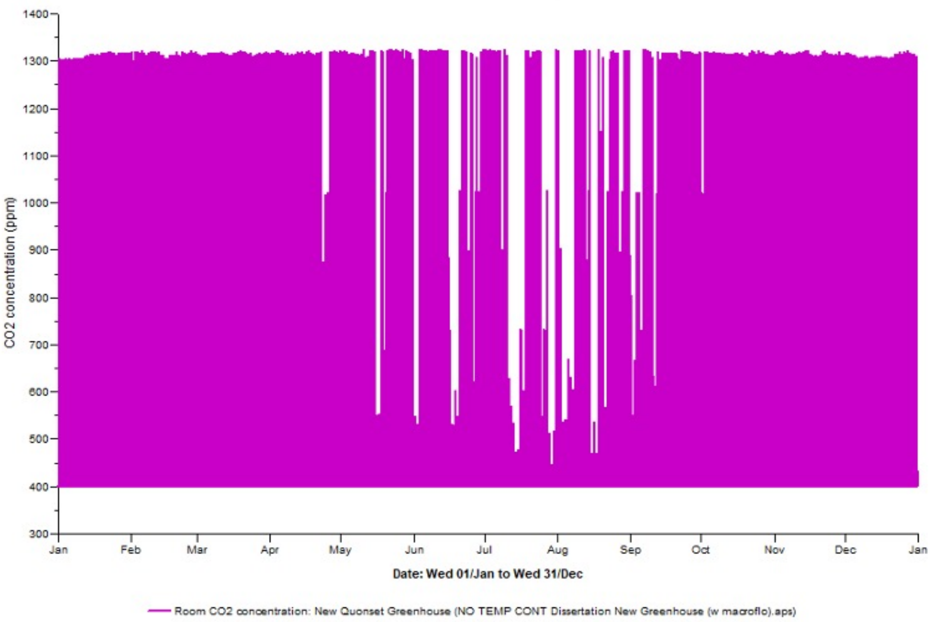

Figure 21. Room Carbon Dioxide Concentration in the Modified Greenhouse (ppm).

Generally, a higher carbon dioxide concentration allows for photosynthesis to take place more often and therefore accelerate plant growth, as long as it is within an acceptable range, which for most greenhouse vegetables tends to be 1500 ppm (Thayer and Eco Enterprises, 2016). However, a carbon dioxide concentration of 1200-1300 ppm for indoor air is considered contaminated and may lead to slight discomfort for human use as well as reduced decision-making and cognitive function (Scully et al., 2019, Zhang et al., 2017), thus ventilation would be required during operating hours in the modified greenhouse.

4.4. PREDICTED MEAN VOTE (PMV)

PMV is a parameter used in thermal comfort to assess and predict the perceived sensation of individuals in a given environment, taking into account various factors that influence comfort, including air temperature, mean radiant temperature, air velocity, humidity, and clothing value (CLO). The PMV is based on a numerical scale, typically ranging from -3 (too cold) to +3 (too hot).

Compared to Figure 22, the modified greenhouse design allows for a tighter range for thermal comfort as seen in Figure 23, as well as preventing the space from being considered too cold under this metric – Figures 22 and 23 having a minimum value of -2 and -1.1 respectively.

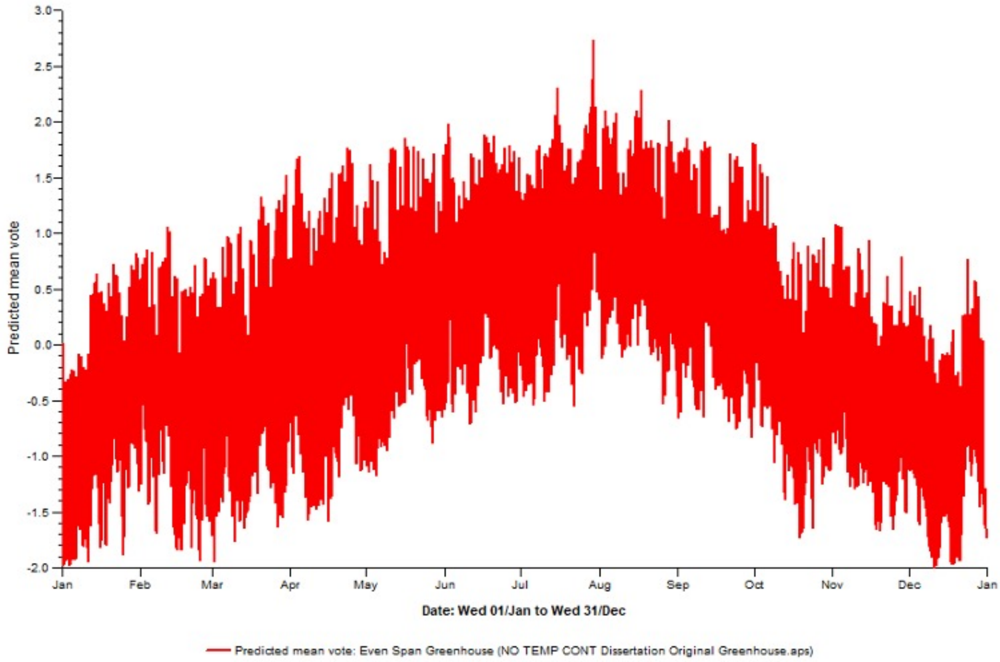

Figure 22. Predicted Mean Vote for Thermal Comfort in the Traditional Greenhouse.

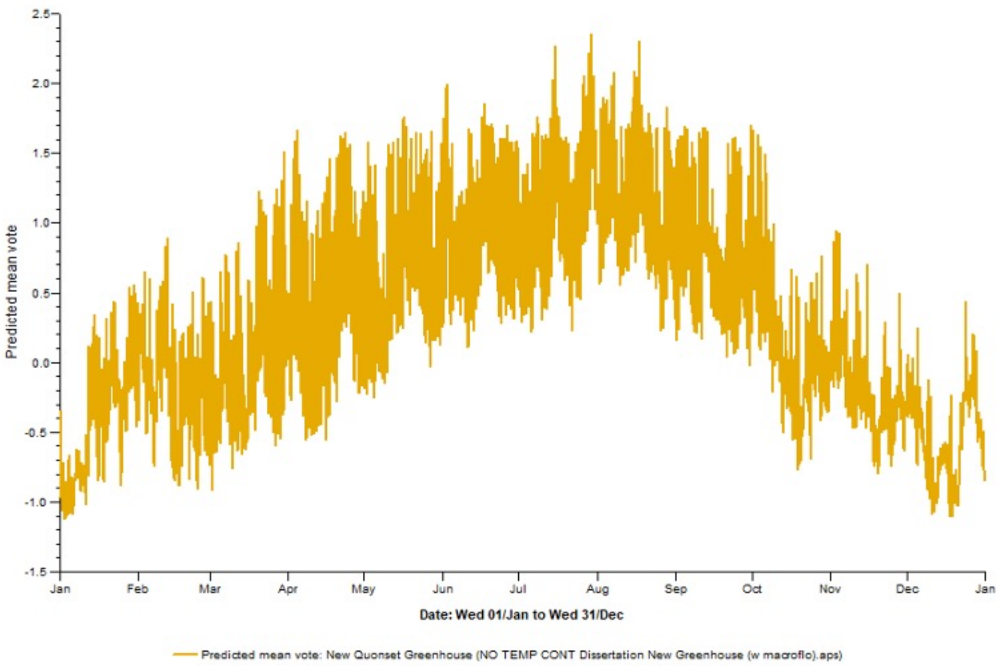

Figure 23. Predicted Mean Vote for Thermal Comfort in the Modified Greenhouse.

Similarly, the PMV value peaks at +2.4 in the modified greenhouse, as compared to the +2.8 in the traditional design. An increase in heat retention between simulations when the vents are closed and a greater opening area in the modified greenhouse when the vents are open as compared to the traditional design is likely the cause of these discrepancies.

4.5. SOLAR GAIN VERSUS EXTERNAL CONDUCTION LOSS

In both Figures 24 and 25, the forms for solar gains and conduction losses mirror each other, since people gains are negligible and internal gains/losses such as infiltration rates and the heat gain from the compost heat recovery system are assumed to be constant.

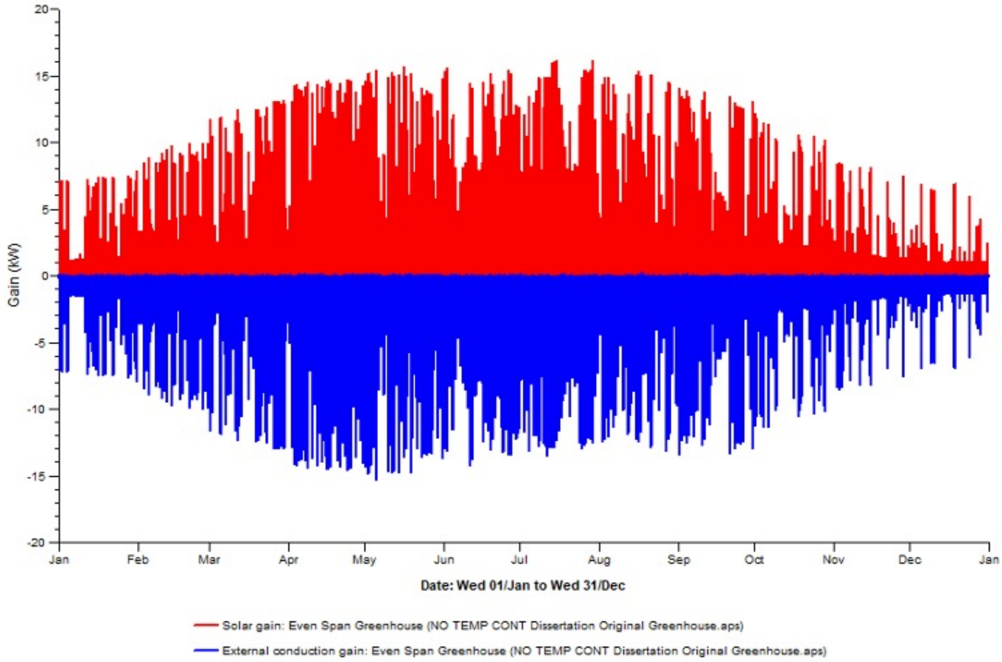

Figure 24. Solar Gains (kW) against External Conduction Loss (kW) in the Traditional Greenhouse.

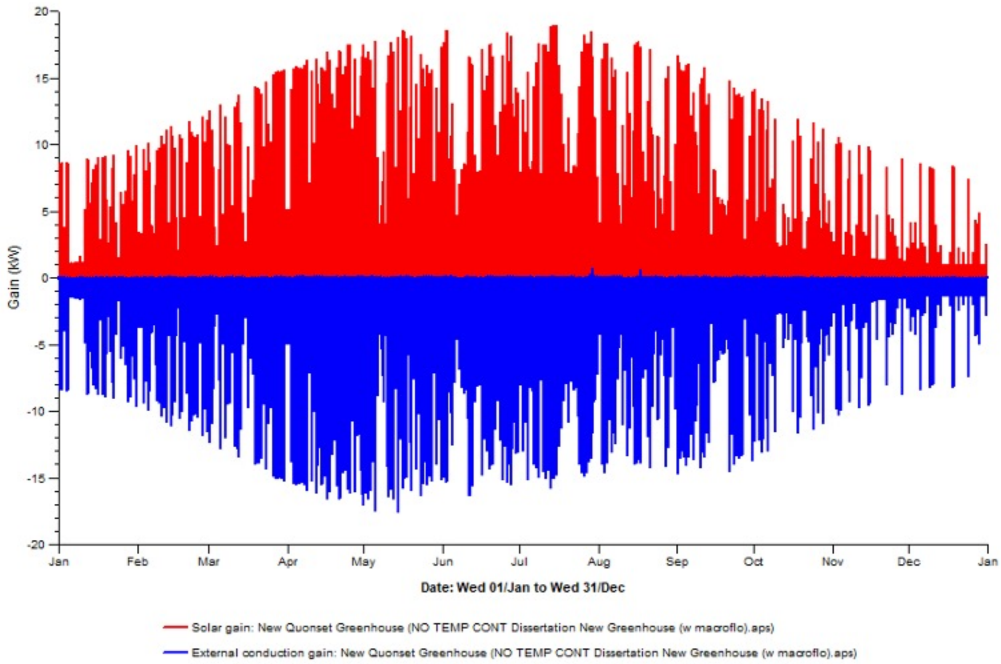

Figure 25. Solar Gains (kW) against External Conduction Loss (kW) in the Modified Greenhouse.

The simulations reported maximum solar gains from both greenhouse designs on the 15th of July, with the traditional greenhouse reporting 16.12 kW of energy being absorbed as compared to 19.79 kW of energy in the modified greenhouse. Similarly, the values of conduction losses at the same time were 12.02 kW and 15.46 kW for the different designs.

Although the modified greenhouse had been optimised to maximise solar gains, the relationship between a high solar gain and comparatively high conduction loss thus suggests negligible improvement in heat retention between simulations – 4.10 kW and 4.33 kW for the traditional and modified greenhouses respectively.

When calculating heat retention over the year however, the difference in values is more evident, with the traditional greenhouse retaining 1.03 MWh while the modified greenhouse retained 1.48 MWh, which demonstrates a 30.4% increase in performance. This difference, when converted to a monetary value at the aforementioned rate of 7.29 p/kWh thus allows for the modified greenhouse to save £32.8 in heating costs.

4.6. TOTAL ENERGY CONSUMED

As mentioned previously, another dataset was created with the implementation of a heating system, so as to better demonstrate the effect the new design has on the ability for a greenhouse to reduce operational costs. In this scenario, both simulations had heating turned off during the summer months of May to September, as depicted by the large gap in the graphs of Figures 26 and 27.

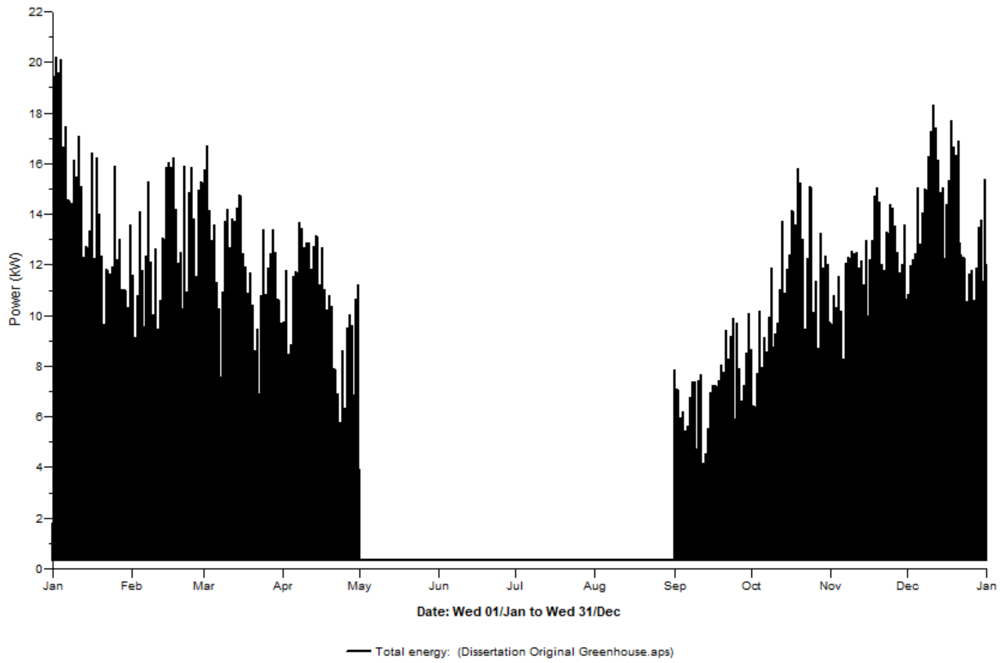

Figure 26. Total Energy Usage (kW) in the Traditional Greenhouse.

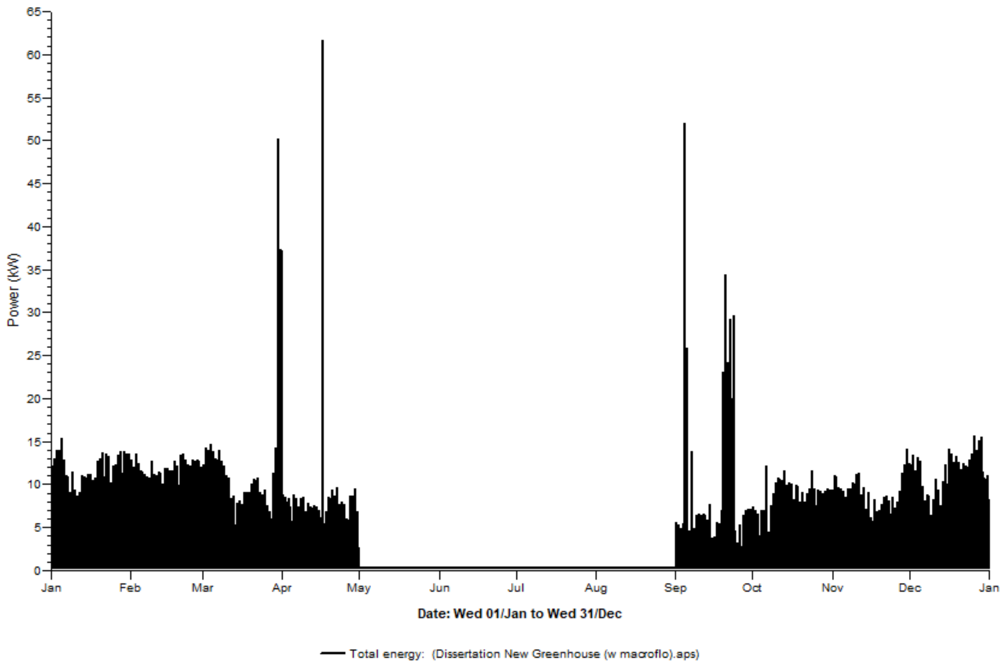

Figure 27. Total Energy Usage (kW) in the Modified Greenhouse.

In the total energy usage graph for the modified greenhouse however, large spikes of energy use can be seen in the Spring and Autumn months, rising to a maximum of 61.63 kW at a given time. These spikes seemed to correspond with a sudden increase in volume flow rate through the opened vents – likely due to the heating system attempting to maintain a certain internal air temperature, but unable to do so since the heated air is moved out of the space at too high a rate, causing the system to attempt the process again. This led to extraordinarily high loads as seen in Figure 27, which in the short term can be solved by manually closing the vents when wind speed is too high, or by modifying the ventilation schedule such that it only triggers during the summer months.

Interestingly, despite these anomalies, the new design still outperforms the traditional greenhouse over the course of the year, with values of 20.77 MWh and 18.79 MWh for the traditional and modified greenhouses respectively. Using the price of gas determined previously (7.29 p/kWh), it is estimated that the modified greenhouse would use £34.24/m^2, as compared to the £37.85/m^2 of the simulated traditional greenhouse, thus seeing an improvement of 9.5%, and saving £3.61/m^2 in heating costs. These values are significantly lower than the national reported cost of £67.5/m^2 for growing protected intensive crops as explored in the introduction chapter, though this may be attributed to horticultural farms diversifying into ornamental crops or other vegetables that may require a warmer environment.

5. CONCLUSION

This study highlights the potential for incremental design optimisation to contribute to the evolution of the UK greenhouse sector, particularly in supporting lower operational costs per unit area and improving the suitability of growing environments for year-round vegetable production. While the performance gains achieved were more modest than initially anticipated, the findings nonetheless point to opportunities for enhancing local food production capacity, especially within community-scale and urban agricultural contexts.

The work also underscores the inherent uncertainties associated with performance prediction based solely on modelling approaches. Climatic variability across the UK and the influence of human and operational factors introduce levels of uncertainty that cannot be fully captured through standardised assumptions. These limitations emphasise the need for caution when extrapolating outcomes beyond the specific conditions represented and reinforce the importance of contextual sensitivity in greenhouse performance assessment.

Future research should therefore prioritise empirical validation through long-term monitoring of physical greenhouse installations across different regions, alongside consideration of social and operational impacts. In particular, understanding how optimised greenhouse designs influence labour demands, productivity, and community engagement would provide valuable insights into their wider applicability and real-world value. Together, such efforts would strengthen the evidence base for low-impact greenhouse design and support more resilient local food systems.

APPENDIX

Figure A1. Detailed photographs of Case Study Greenhouses.

The greenhouses examined at the allotment used an aluminium frame with thin polycarbonate panes to house the vegetables within; however, the gothic arch greenhouse only had one sidewall vent at the back of the structure, away from any prevailing winds; while the even-span gable utilised two roof vents as seen in the above image.

Both greenhouses were underutilised, with few if not no vegetation being grown despite the photos taken long before the winter months.

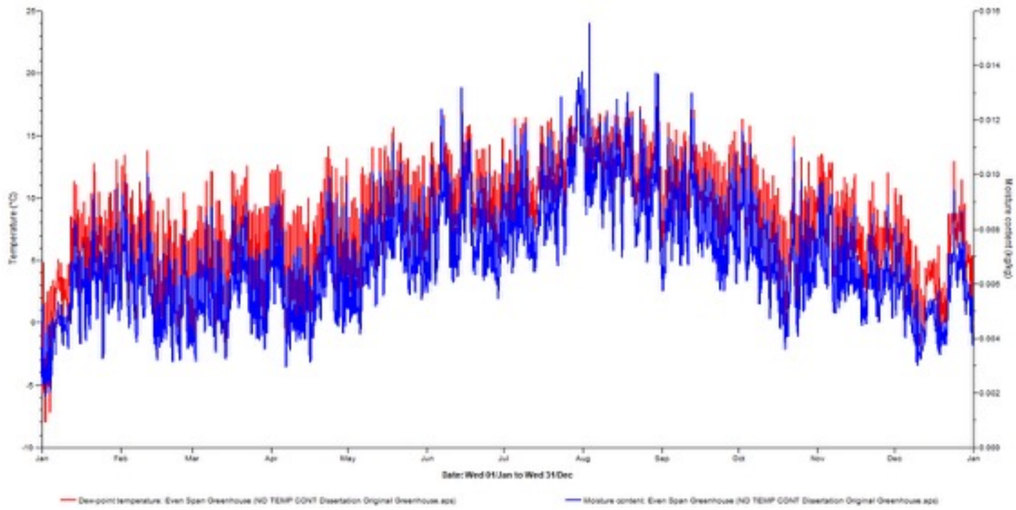

Figure A2. Dew-point Temperature (°C) against Moisture Content (kg/kg) in the Traditional Greenhouse.

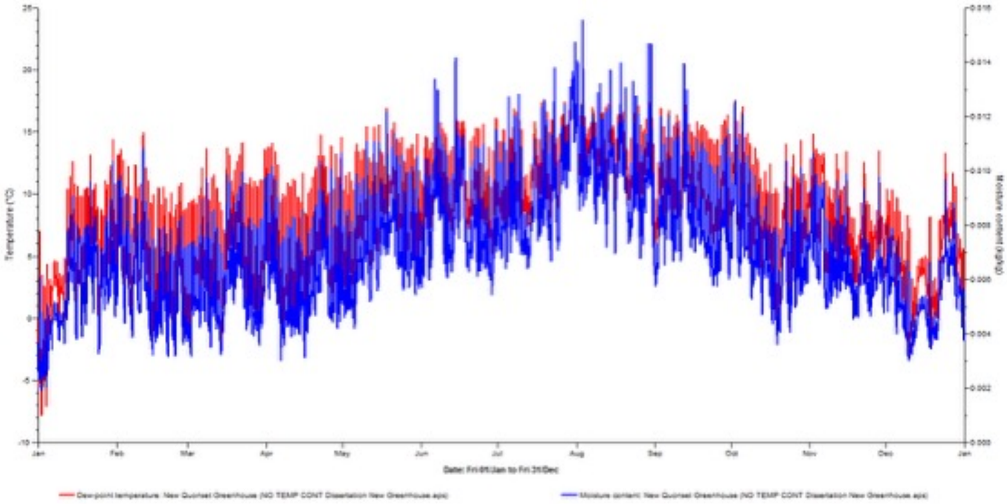

Figure A3. Dew-point Temperature (°C) versus Moisture Content (kg/kg) in the Modified Greenhouse.

Generally, the dew-point temperature and moisture content in the modified greenhouse is higher than the original greenhouse, however that is likely due to increased internal air temperatures in the modified design. Since warmer air tends to be able to hold more moisture, as the temperature increases, the capacity for the air to retain water vapour also increases, thus resulting in a higher dew-point temperature.

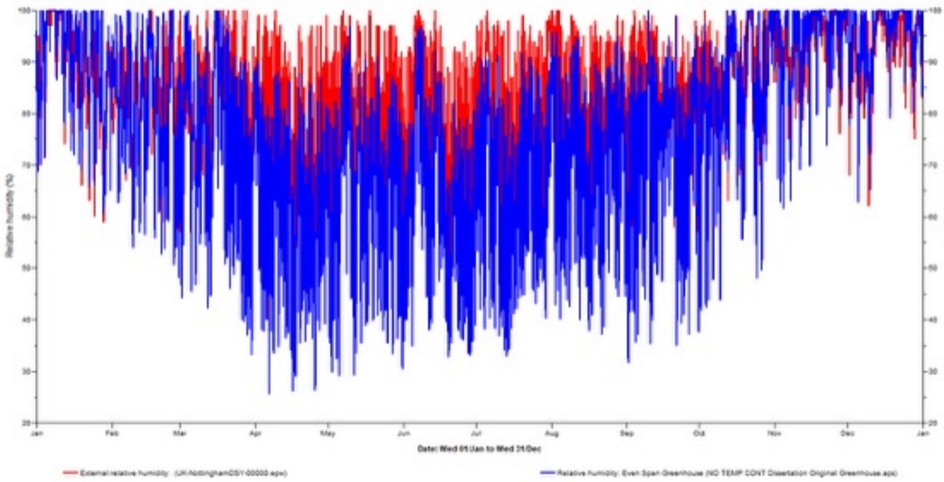

Figure A4. Relative Humidity comparison between the external and internal air of a Traditional Greenhouse.

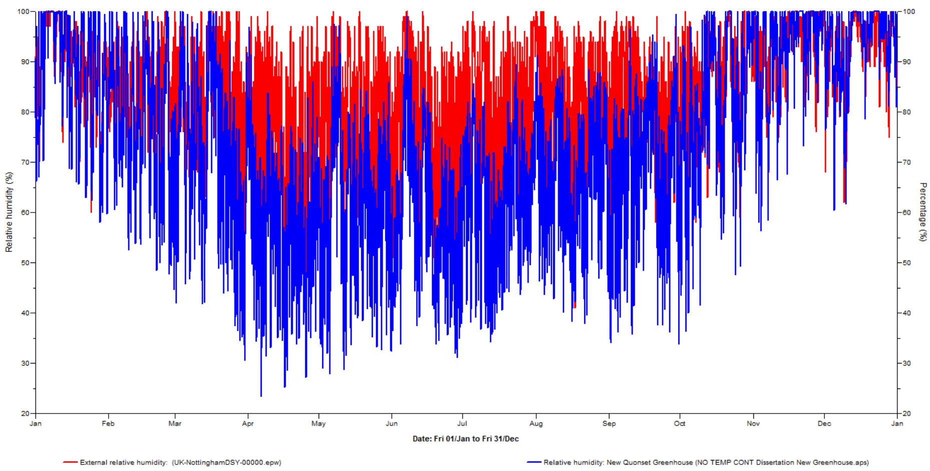

Figure A5. Relative Humidity comparison between the external and internal air of a Modified Greenhouse.

The modified greenhouse has a lower internal relative humidity as compared to the traditional greenhouse, though this is likely due to an increase in the number of vents, thus increasing opening area and thereby allowing more air flow through the space, as seen in Figures 18 and 19. The relative humidity values in the modified greenhouse also tend to be better for greenhouse vegetables, since they are non-tropical plants and thus require a less humid environment, as well as reducing breakouts of mould within the space.

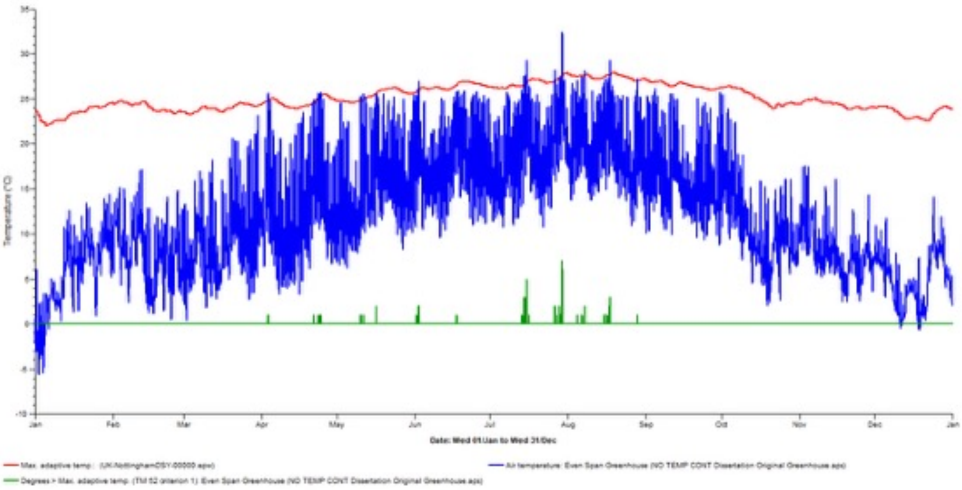

Figure A6. Air temperature (°C) within the Traditional Greenhouse against max. adaptive temperature (°C).

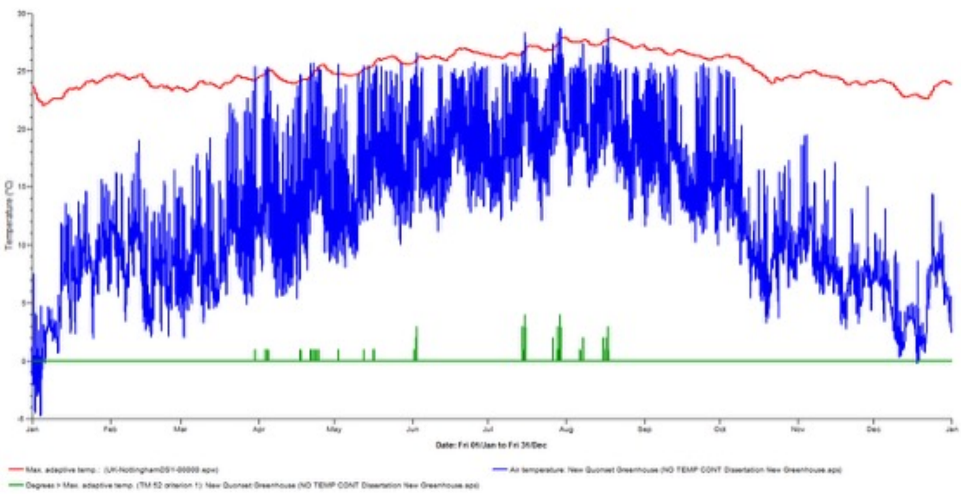

Figure A7. Air temperature (°C) within the Modified Greenhouse against max. adaptive temperature (°C).

Maximum adaptive temperature refers to the highest temperature at which individuals can still maintain thermal comfort through behavioural adaptations, such as adjusting clothing, seeking shade, or altering activity levels. These graphs compare this value to the internal air temperature of the greenhouses throughout the year, and the magnitude of how much the maximum adaptive temperature is exceeded at any one time is given by the green curves, allowing for a clearer understanding of how much the modified greenhouse allows for more thermal comfort.

AUTHOR CONTRIBUTIONS

Xiaofeng Zheng: Conceptualization, Supervision, Writing – review & editing. **Kieran Joshua Lim**: Conceptualization, Investigation, Formal Analysis, Writing – original draft.

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COMPETING INTERESTS

The authors declare they have no competing financial interests or personal relationships that may have influenced the work reported in this paper.

DATA ACCESSIBILITY

The data generated during this study are available from the corresponding author upon reasonable request. Sources used for the literature review are publicly available and are cited in the reference list.

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