Journal of Cleaner Production 432 (2023) 139650

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Synergy between industry and agriculture: Techno-economic and life cycle assessments of waste recovery for crop growth in glasshouses

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ARTICLE INFO

Handling Editor: Xin Tong

Keywords:
CCUS
Industrial wastes
Greenhouse crop cultivation
Circular economy
Techno-economic-environmental analysis

ABSTRACT

Controlled-environment agriculture in agro-industrial systems, where carbon dioxide, heat, and other wastes are recovered or recycled, has potential to be an environmentally friendly approach with economic feasibility. However, such approaches need careful exploration to ensure that environmental and economic benefits are maximised. Techno-economic, and life cycle assessments were applied to evaluate the synergy of producing crops (tomato and hemp) and recovering industrial wastes (e.g., heat and carbon dioxide) in glasshouses with robust uncertainty and sensitivity analyses. For each crop, two scenarios were compared, linear scenarios evaluated the use of raw materials with no waste recovery whereas circular scenarios captured industry flows and reused or recycled them in the glasshouse- avoiding raw materials consumption. Circular practices had a net benefit on the global warming potential for both crops, capturing up to 50,000 kg/y of CO_2 in crops biomass and providing competitive product prices. The analysis showed that circular operational conditions can reduce, by almost half, the break-even product selling prices and sequester up to, approximately, 500 kg $CO_{2eq.}/m^2$ of glasshouse if compared to linear systems. Future investments in this outstanding strategy to supply the United Kingdom's market demand of tomatoes could lead to a low-cost product and negative $CO_{2eq.}$ emissions by mitigating the importation of these products. Alongside, other impact categories scores may not be as favourable as the global warming potential, due to high impact of the waste management phase, chemical fertilisers, and pesticides utilisation.

1. Introduction

Utilisation of wastes could be a significant opportunity to benefit the decarbonisation of industrial clusters. In 2020 the United Kingdom (UK) commercial and industrial sector generated 33.8 million tonnes of waste (DEFRA, 2022). The majority of this (18.7 million tonnes, ~55%) ends up in landfills around the country. Carbon dioxide (CO_2) and another industrial process gases are also a form of waste with ~84.5 million tonnes emitted in the UK each year (BEIS, 2022, 2023). Fig. 1 shows the availability of material wastes and treatment capacities within the South Wales Industrial Cluster (SWIC) - the region of interest in this study. In addition to material wastes, energy losses through heat (Wang et al., 2023) and light (Górecki et al., 2019) must be highlighted. For example, the Port Talbot Steelworks in SWIC produces enough waste heat energy each year to supply heat 500,000 homes (Cooper et al., 2016; Sullivan, 2020). Valorisation of these industrial streams could generate additional revenue, partially compensate the costs of decarbonisation, and delay emissions of the embodied carbon, providing new economic and environmental life cycles for the former wastes. Therefore, the use of bio-based mechanisms to support agricultural business and industrial clusters in decarbonisation was explored by harnessing the capability of carbon capture use and storage (CCUS) during crop's growth to mitigate emissions from the most difficult-to-decarbonise industrial clusters.

The use of glasshouses could provide a promising solution to industrial waste utilisation in some operational conditions. Crops in the glasshouses can convert industrial CO_2 waste flows into biomass during

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https://doi.org/10.1016/j.jclepro.2023.139650
Received 7 July 2023; Received in revised form 30 October 2023; Accepted 6 November 2023

their growth and waste heat can be used to maintain optimal temperatures. Bio-wastes can be composted and used as growth medium and recycled materials can be used in both construction and structural maintenance of the glasshouse. The potential of cultivating two crops was evaluated as a pathway to support industrial decarbonisation: tomatoes – an economically important crop with 400–500 million GBP imported each year to the UK (International Trade Centre, 2022) – and hemp – which has a myriad of uses including as a food and fibre source (Tsaliki et al., 2021). These crops were selected as they allow the exploration of contrasting production systems, product values, and temporal carbon storage. The storage time of carbon in the products could vary before consumption from short term storage (several weeks) for fresh tomatoes fruits to years or decades for hemp fibers when they are used in clothing or construction materials, respectively (Shang and Tariku, 2021; Wiedemann et al., 2020).

Evidence of growing both tomatoes and hemp in controlled environments is widespread. In the European Union, 31% of tomato production occurs in glasshouses (Xue et al., 2020). By switching to domestically grown tomato in UK, the impact from the transport stage can be significantly reduced during its importation. If grown at scale, this could also reduce some of the supply chain issues faced in the UK in 2022 and 2023 (ONS, 2023). The global hemp market is growing, Terra Tech Corporation, Hemp Inc., and British Sugar are examples of commercial producers. Pulkoski and Burrack (2023) report that nearly 1.5 million square meters of hemp were grown in glasshouses in 2021 only in the USA.

The recovery of industrial wastes (e.g., heat and CO_2) associated with glasshouses could be promising since it allows plant cultivation in a highly controlled environment and increased productivity in colder climates as crops can be grown all year round. The CO_2 levels, heat, moisture, and nutrients can be finely controlled to optimise crop growth and minimise resources use. Elevated CO_2 in glasshouses is a well-established practice with levels of 1000–1300 ppm being optimal (Blom et al., 2002), which is around three times that of atmospheric CO_2, which was 419 ppm in January 2023 (NOAA, 2023). Sourcing of CO_2 can be costly, and trade prices have been impacted by supply chain issues resulting from rising gas prices (BBC News, 2021). Introducing CO_2 from industrial processes to sealed glasshouse, could avoid exposure to fluctuations in trade price, and allows for the utilisation of a waste stream that would otherwise end up emitted to the atmosphere, and likewise for waste heat.

A full techno-economic-environmental analysis was undertaken to identify eco-friendly opportunities of investment between farming and industrial sectors for SWIC decarbonisation. The life cycle assessment (LCA) and the techno-economic analysis (TEA) with global sensitivity (SA) and uncertainty analysis (UA) were combined for robust modelling. Statistical tools were combined with the TEA and LCA to identify the main opportunities and flaws of growing crops in glasshouses as a bio-based carbon capture strategy for supporting UK's industrial decarbonisation and the circular economy development.

2. Methods

2.1. Scope

Environmental and economic aspects of recovering wastes into glasshouses for cultivating valuable and high market-demand crops were evaluated. To enable the comparison of both economic and environmental performance of glasshouses as a strategy for carbon capture and its storage in distinct crop products, the functional unit of 1 m^2 of glasshouse area was used. Tomato (T) and hemp (H) were selected to evaluate the CCUS operation of glasshouses to mitigate environmental burdens of agro-industrial wastes.

The cultivation steps in these assessments included: seeding, growth, processing, product hauling, wastes disposal and others. Hemp fibre, fresh tomatoes, and hemp seeds were produced. Two scenarios for each crop were considered: linear (T_L, H_L) and circular (T_C and H_C). Linear scenarios where CO_2 was sourced from compressed CO_2 cylinders, heat was provided by electrical heaters powered by UK national grid electricity mix. All wastes in this scenario were assumed to end up in local landfill sites at the end of each growth period. Water was taken from municipal water supplies in linear scenarios. Wastes were recovered and

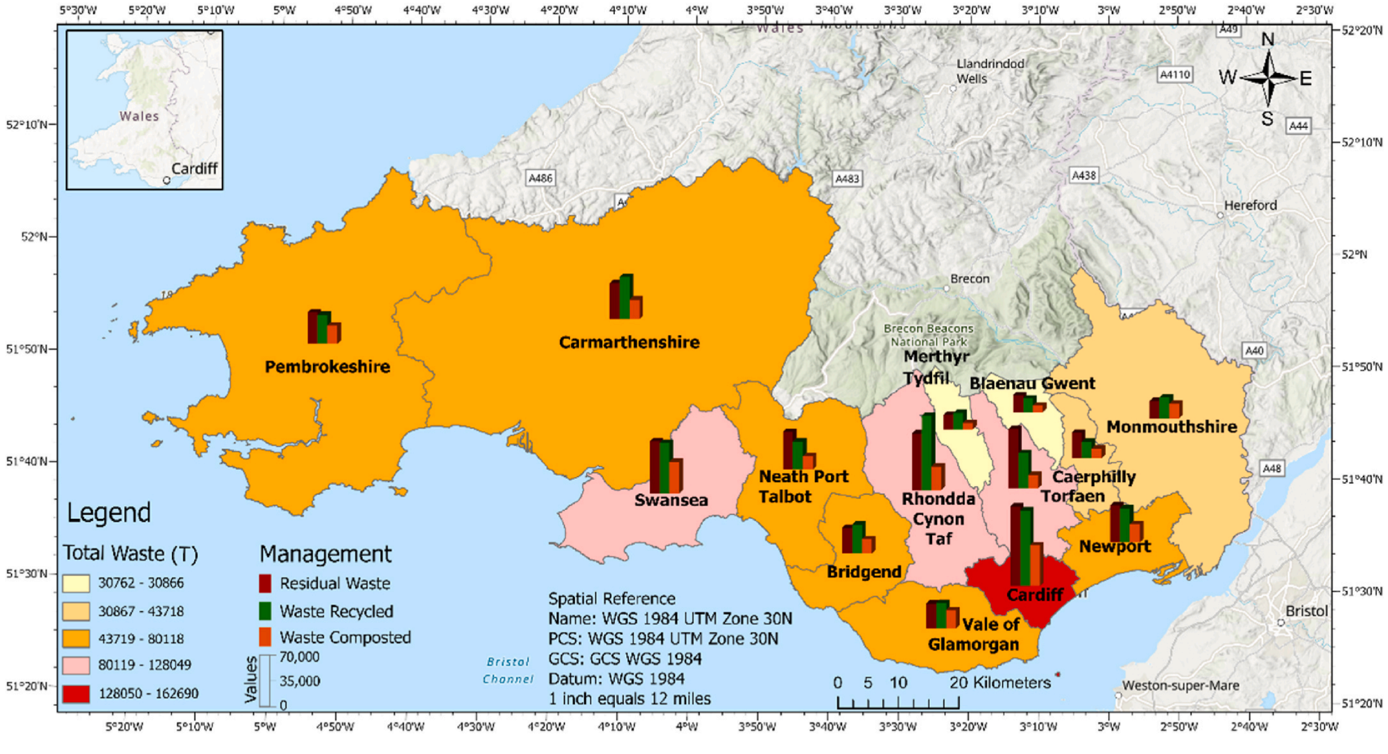

Fig. 1. Management facilities and quantity of wastes in SWIC and adjacent council zones.

recycled for use in the subsequent growing season in circular scenarios. Plastics and metals from the glasshouse were assumed to be reprocessed at local facilities and plastics entering the glasshouse in subsequent years were produced from recycled materials. The circular scenarios considered CO_2 and heat sourced from industrial waste streams - such as from the steel making process, which produces both simultaneously and is one of the largest emitters within SWIC. Water was recovered from groundwater and rainfall in circular operational conditions. Harvesting wastes were treated at the end of each growth cycle, inorganic wastes such as plastics and metals were recycled in the subsequent growth cycle and biomass wastes were converted to biochar through pyrolysis, which was not currently practiced in SWIC at large scale but has the potential for long-term storage of the carbon (Papageorgiou et al., 2021; Zaini et al., 2021). All industry-sourced wastes were modelled in LCA as burden-free flows. Crop yields and biomass were assumed to be unaffected by the scenarios.

The material and financial requirements to construct the glass house were adapted from Canales Medina and Snyder (2020) to build a glasshouse on industrial land in SWIC. The CO_2 was constantly dispersed within the glasshouse to ensure that levels were between 1000–1300 ppm for optimal production of carbohydrates (Blom et al., 2002). Lights were installed to provide adequate lighting for high plant growth year-round. Additional information about the glasshouse structure was provided in the Supplementary Material (SM). The lifespan of the glasshouse was 20 years with new seedlings sown each year. At the end of life of the glasshouse, the plastic walls and steel were also recycled.

The carbon stored in the biomass was determined by the total amount of biomass minus the amount of biomass being sent to waste treatment/disposal. For tomatoes the amount of carbon accumulated in the biomass was assumed to be re-emitted at the end of each growth cycle as the fruit was consumed and the remaining biomass was disposed of. Hemp retains a fraction of the carbon in the fibres for extended periods (50+ years) which are assumed to outlast the lifespan of the glasshouse (20 years) when used in construction materials (Shang and Tariku, 2021). For this reason, the ultimate disposal of hemp fibres was not considered.

Consequential LCA was used to assess different scenarios as it considers the competition for resources in supply chains. The circular scenarios were used as counterfactual operational condition of linear approaches. The system boundary was selected as cradle-to-grave to understand how different crops could change the potential of glasshouse to be used as an industrial decarbonisation strategy. Fig. 2 shows all foreground and background process of the system boundaries.

2.2. *Techno-economic assumptions*

The net present value (NPV) was used to assess the economic feasibility of the scenarios (Towler and Sinnott, 2021). All the projections assumed a minimum acceptable rate of return of 6% (WSGA, 2009). The Straight-line method was used to estimate the glass house depreciation for 9.5 years (Towler and Sinnott, 2021). Taxes varied with the net profit – value added tax (VAT) was considered as part of the product price since it could vary accordingly with the product (HM Treasury, 2022). For the hemp production a license fee of £580/year (THC $\leq$ 0.2%) was included (Misuse of Drugs Act, 1971; 2001) with additional costs for laboratory analysis (Harper et al., 2018; Home Office, 2012). The operational cost of the recovered CO_2 and heat were assumed to be none. The disposal of wastes was modelled as extra operational costs.

2.3. *Uncertainty and sensitivity analyses*

Uncertainty analysis was conducted by first determining the uncertainties of the input datasets. Pedigree matrices were created for each of the six glasshouse phases, based on the reliability (U_1), completeness (U_2), temporal correlation (U_3), geographical correlation (U_4), technological correlation (U_5) and a basic uncertainty (U_b) based on the type of process, the definitions of which were provided by Ciroth (2012). These pedigrees were then used with the suggested values for their score from and the geometric standard deviation (Equation (1)) to determine the upper and lower bounds of uncertainty.

$$SD_{g95} = \sigma_g^2 = e^{\sqrt{\ln (U_1)^2 + \ln (U_2)^2 + \ln (U_3)^2 + \ln (U_4)^2 + \ln (U_5)^2 + \ln (U_b)^2}} \tag{1}$$

The input uncertainty was propagated to the output through performing quasi-Monte Carlo simulations with changes in inputs between the lower and upper bounds. Sobol' sampling, a quasi-random low discrepancy sequencing method, was used to generate the parameters for each input such that the uncertainty domain was utilised efficiently

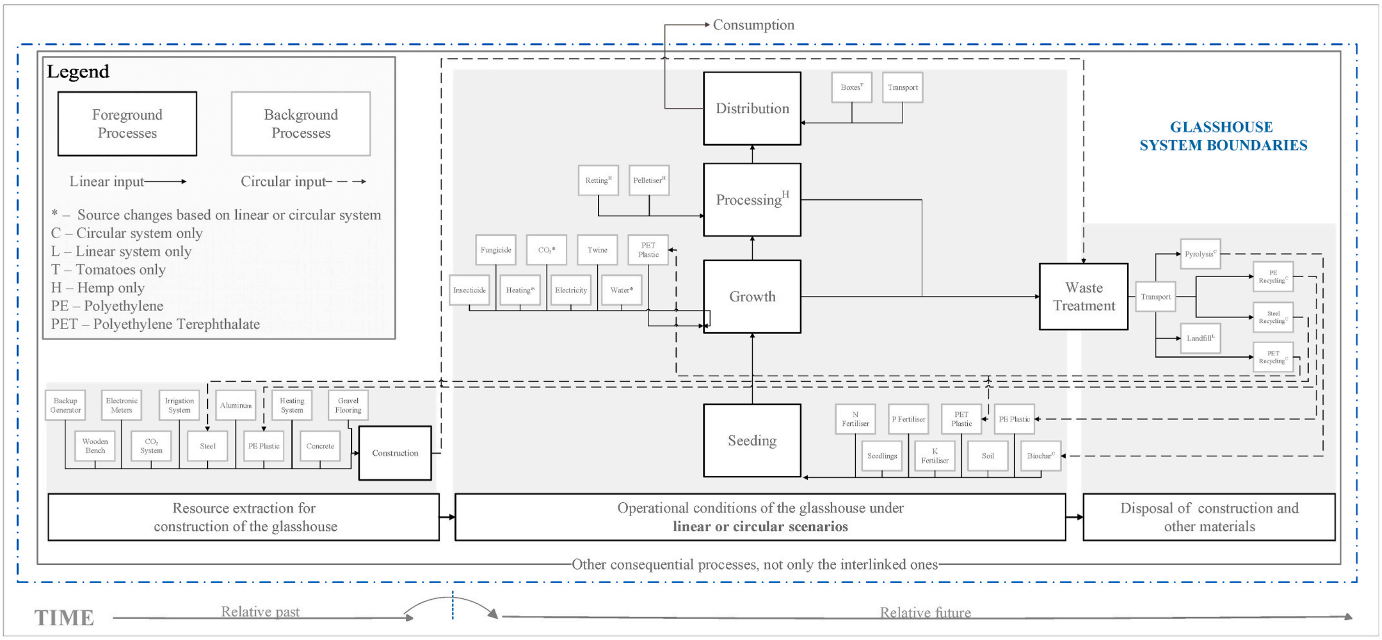

Fig. 2. System boundaries of consequential LCA for the life cycle of 1 m^2 of glasshouse. Illustration based on the definition of consequential LCA in ISO (14040–14044) according to Schaubroeck et al. (2021).

(Blatman et al., 2007).

Sensitivity analysis was performed with the same data of uncertainty. The first order sensitivity indices for each of the crop phases were then calculated by the Sobol' method. Saltelli et al. (2008) provide a complete derivation of first order indices and how the method calculates them for a given input.

The uncertainty and global sensitivity analysis was also applied on the TEA by considering variations of ± 15% on the product yields, OpEx of each production stage and the total project investment. In total 20,480 samples were used for each scenario. The application of the uncertainty and sensitivity analysis was essential since the estimates considered the combination of different literature sources, which could lead to high level of uncertainty on the yields estimates and costs inferences.

2.4. Inventory

The inventory was divided into six categories: Construction – where the glasshouse and equipment were assembled and maintained. The glasshouse life span was 20 years (WSGA, 2009). The structure was built once per lifespan (in the 0th year), while some pieces of equipment were assumed to need replacing every 2–10 years, see Canales Medina and Snyder (2020) for equipment and replacement times; Seeding – where beds were prepared with soil and fertilisers before seedlings were planted; Growth – supply of CO_2, heat and water, to the plants, fungicides and pesticides applications, and labour for pruning, harvesting, etc.; Distribution – The crops were transported to their intermediate destination, in the case of hemp fibre and seed processing, and final destinations; Wastes – The processing of all growing wastes including both inorganics and organics, in the final year (20th) this also includes the dismantling and disposal of the glasshouse; and Processing – Applies only to the hemp, the process of transforming the biomass into fibres through retting (Magnusson and Svennerstedt, 2007).

Crops are proposed to be grown in an expanded perlite soil in a shared bed. The crop density, lighting period, water and nutrients vary between tomatoes and hemp (Deng et al., 2019; Sanyé-Mengual et al., 2015). Losses were neglected at the use stage. The production considered 250 working days with 80% of useful time, totalling 4800 h per year. All materials and inputs were supplied from the UK with a road-transport distance of 50 km for locally sourced (within SWIC) materials as recommended by RICS (2017) for construction materials.

The mass, energy, and costs inventories were estimated from literature reports. Tables 1–4 summarise the shared estimates for TEA and LCA of this study.

2.5. Software and libraries

All analysis and plots were produced in Python 3.9 (Van Rossum and Drake Jr, 1995) with the Matplotlib (Hunter, 2007) library used for visualisations. Uncertainty and sensitivity analysis were conducted with the SALib library (Herman and Usher, 2017; Iwanaga et al., 2022) for sampling and sensitivity index calculation. Brightway2 (Mutel, 2017) was used for LCA calculations and biosphere flows. Ecoinvent 3.8 consequential database was used for inventory data. SM provides the names of the datasets used for all background process. Twenty-six impacts were assessed with characterisation factors from Environmental Footprint v3.0. This database, developed as part of the European Commission's Single Market for Green Products Initiative, uses European characterisation factors for environmental and human health impacts (European Commission, 2021).

3. Results & discussion

3.1. Life cycle assessment

Overall, the circular scenarios showed beneficial impacts for the GWP and MEP, where the carbon capture during plant growth in the circular scenarios contributed to the mitigation of the environmental impacts - as is shown in Fig. 3. Across the stages, the seeding phase was the largest contributor to detrimental impacts. This was largely driven by the environmental and health effects of manufacturing and applying the fertilisers in this phase. The difference in seeding impacts of tomatoes and hemp was due to the quantities of fertilisers required, which was ~16x higher for tomatoes as shown in Tables 1 and 2 The waste treatment methods in T_C and H_C were also a significant contributor to many of the impact categories due to the energy and materials required to collect, sort, and process the wastes for reuse. These impacts exceeded the potential environmental impacts of processing virgin materials for

Table 1
Technical and economic inventories per year of tomatoes.

Input/Output	Quantity		Reference	Price		Reference
Tomato growth cycles	4800	hours (3/y)	(Engindeniz, 2006; Sanyé-Mengual et al., 2015)			
Plant spacing	2	plants/m^2	Sanyé-Mengual et al. (2015)			
Average seeded area	580.320	m^2	Sanyé-Mengual et al. (2015)	0.010	GBP/m^2	Hu et al. (2019)
Fertilisers			Sanyé-Mengual et al. (2015)			
Nitrogen	2.93	kg/m^2		0.008	GBP/m^2	
Phosphate	0.19	kg/m^2				Engindeniz (2006)
Potassium	0.06	kg/m^2				
Pesticides	0.01	kg/m^2		0.014	GBP/m^2	
Water (rain or tap)	2.39	kg/m^2	Sanyé-Mengual et al. (2015)	98 GBP/year (service fee) + +2.034 GBP/m^3 (<20000m^3)+ +1.66 GBP/m3 (>20000m^3)		WWSL (2022)
Energy				0.102	GBP/kWh	Canales Medina and Snyder (2020)
Lighting[a]	5.10	kwh/m^2	(Georgiou et al., 2018)			
Electricity						
Glasshouse acclimatization	5.93	kwh/m^2				
CO_2 consumption	20.30	kg/m^2	Hu et al. (2019)	1.969	GBP/kg	(BBC News, 2021)
Hauling	50	km	Hu et al. (2019)	1.035	GBP/ton-km	Sanyé-Mengual et al. (2015)
Fruit Yield	29.70	kg/m^2	Hu et al. (2019)	2.280	GBP/kg	Department for Environment, Food & Rural Affairs, UK (DEFRA, 2021)

[a] Total of 16 h/day.

Table 2
Technical and economic inventories per year of hemp.

Input/Output	Quantity		Reference	Price		Reference
Hemp growth cycles	3600	hours (3/y)	Deng et al. (2019)			
Plant spacing	35	plants/m^2	Deng et al. (2019)			
Seeded area	580.320	m^2		0.015	GBP/m^2	(Duque Schumacher et al., 2020)
Fertilisers			Deng et al. (2019)			
Nitrogen	0.078	kg/m^2		0.228		(Duque Schumacher et al., 2020)
Phosphate	0.027	kg/m^2			GBP/m^2	
Potassium	0.069	kg/m^2				
Pesticides	0.012	kg/m^2	Canales Medina and Snyder (2020)	0.014	GBP/m^2	Engindeniz (2006)
Water (rain or tap)	44.886	kg/m^2				
Growth	0.066	kg/m^2	Gill et al. (2022)	98 GBP/year (service fee) + +2.034 GBP/m^3+ +(<20000m^3) ++1.66 GBP/m^3 (>20000m^3)		WWSL (2022)
Green decortication	44.82	kg of water/m^2	Turunen and van der Werf (2007)			
Energy				0.102	GBP/kWh	
Lighting[a]	5.10	kwh/m^2	(Georgiouet al., 2018)			
Electricity						
Glasshouse acclimatization	5.93	kwh/m^2				
CO_2 consumption	25.596	kg/m^2	Tang et al. (2017)	1.969	GBP/kg	(BBC News, 2021)
Hauling						
Fibre	50	Km		0.303	GBP/ton-km	Harper et al. (2018)
Seed (grains)				1.035	GBP/ton-km	
IH THC testing fee	1			0.001	GBP/m^2	Harper et al. (2018)
Total biomass[b]	6.723	kg/m^2	Deleuran and Flengmark (2006)			
Fibre	1.5		Struik et al. (2000)	1.500	GBP/kg	Tsaliki et al. (2021)
Seed pellets	0.78		Tsaliki et al. (2021)	18.33	GBP/kg	Harper et al. (2018)
Equipment-hire for fibre and seed processing[b]				200–900	GBP/week	

[a] Total of 12 h/day.
[b] Estimated value.

Table 3
Technical and economic inventories for the waste management per year for both crops. Pyrolysis and landfilling were considered as biomass waste management.

Input/Output	Quantity		Reference	Price		Reference
Liquids effluents (3 people – office staff)	152	L/person/day	Estimate	1.630	GBP/m^3	WWSL (2022)
Transport of solid wastes to the treatment plant	50	km	Estimate	0.005	GBP/m^2 (Transport-lorry 16-32t)	Sanyé-Mengual et al. (2015)
Solids disposal						
Tomato wastes[a]	16.335	kg/m^2	Zhu et al. (2022)	0.07	GBP/ton	Kwan et al. (2015)
Hemp wastes[a]	2.694	kg/m^2 (5% of total biomass yield)	Olan et al. (2022)			

The fibre transported without bailing. Tomatoes, seed pellets were transported with reused boxes.
[a] The treatment of the agricultural wastes was charged.

many of the impacts categories (Fig. 3). Interestingly, the circular scenarios mitigated the waste management contribution only for hemp for the global warming potential over a 100-year time horizon (GWP), ozone depletion, and photochemical ozone formation since this crop generated less organic matter to be processed and the recovery of the heat and CO_2 industrial flows were more relevant.

The most important impacts for the scenarios were determined to be the GWP, depletion of energy resources, depletion of metals and minerals, land use/land use change, and water use. These impacts after one year of crop growth are shown in Fig. 4 and after twenty years in Fig. 5. Circular systems have a lower GWP and metal and mineral depletion than their linear counterparts as shown in Fig. 4-a, -c and Fig. 5-a, -c, mainly due to energy savings after the heat recovery and CO_2 consumption during the plants growth. Most of the other environmental impact scores were not mitigated by the circular strategies. This result could be explained by extra waste processing stages to enable the reuse of resources for the subsequent year's crop. The production of biochar from the biomass was particularly impactful due to the heat required for pyrolysis, while using the biochar as a soil amendment had insignificant benefits within the system boundaries of this LCA as the soil is changed each year to prevent pathogens.

The linear systems provided a higher GWP impact than their circular counterparts due in part to the source of CO_2 needed to optimise plant growth and from the use of grid energy for heating (Fig. 4-a and Fig. 5-a). For comparison, the circular scenarios use CO_2 from industrial flue-gas and recovered heat. The circular hemp scenario was by far the most beneficial in this impact due to the storage of carbon in the biomass, more of which was utilised than the tomatoes, where only the fruit was used, coupled with the use of recovered energy and wastes leads to an overall all negative GWP for this scenario. Therefore, each year there was a net capture of CO_2 by the hemp over the 20-year life span of the glasshouse. Circular assumptions such as the use on rainwater on the

Table 4
Modelling the products processing before selling.

Processing		Energy demand	Unit	Reference
Retting	10.800	kWh/kg (75% of efficiency)		Turunen and van der Werf (2007)
Drying	Fibre	2.116	kWh/kg of retted biomass	Turunen and van der Werf (2007)
	Seed	0.115	kWh/kg of wet seed	Olan et al. (2022)
Grinding	Seed	0.026	kWh/kg of seeds	Turunen and van der Werf (2007)
	Fibre	13.440	kWh/kg of dried biomass	
Soft scutching Pelletiser	Electricity	0.009	$kWh/m^2/y$	Turunen and van der Werf (2007)
	Heat	0.084	$kWh/m^2/y$	
Total biomass loss		16	% (w:w, dry basis)	Turunen and van der Werf (2007)
	Fibre	0.15	kg/m^2 (6%)/y	
	Dust-particular matter	0.090	kg/m^2 (10%)/y	

system instead of tap water, lower utilisation of fertilizers, led to lower processing of inputs, which also contributed to the reduction of the overall CO_{2eq}.

As the circular systems required more processing of wastes through recycling, they led to an increase in the energy resource depletion, as shown in Fig. 4-b and Fig. 5-b. Even with the reduction in energy from the circular systems heating being supplied by industrial waste heat, they require more energy for recycling than was recovered.

The depletion of minerals and metals (Fig. 4-c and Fig. 5-c) between the scenarios of the same crop remain largely the same. However, when comparing tomatoes to hemp the tomatoes require more materials each year than the hemp, hence the increase in metal and mineral consumption compared to hemp.

The land use and land use change (Fig. 4-d and Fig. 5-d) varies between each scenario as it accounts for more than just the physical occupation of a glasshouse on land. The linear systems have lesser impact than their circular equivalents. This was due to the increase in the number of processes required in the recycling processes as well as the emissions to soil and changes to the quality of land from those processes and the sites that they occupy.

The water use (Fig. 4-e and Fig. 5-e) once again the linear systems have a lower impact than their respective circular counterpart. The tomatoes water use was significantly more than those of hemp. Interestingly the linear hemp system's impact crosses the zero mark around the eighth year, this was thought to be from the reduced fertilisers and irrigation water compared to the tomato crops. Additional impact categories can be found in the SM.

The range of uncertainty of the GWP for each scenario was shown in Fig. 6. The distribution of the uncertainty was large for all scenarios due to the considerable number of inputs to the glasshouse, each having large uncertainties of their own. For all scenarios except H_C, a positive CO_2 eq. was the most likely result. This indicated that the scenarios were not suitable as carbon negative or neutral options. H_C had a higher probability of being a carbon negative solution, although the large portion of the distribution greater than zero cannot be ignored. Therefore, the adoption of these technologies needs careful consideration by decision makers to reduce the positive $CO_{2eq.}$ contributing inputs. Inputs such as phosphorus and potassium fertilisers, among others contribute, significantly to the uncertainty as the datasets used were not geographically representative of UK production leading to higher SD_{g95} when Equation (1) was used to calculate input uncertainties. This is a limitation of the database used, where UK or European production of these inputs were not available. The same limitation also applied to the other sources of uncertainty that contribute to each input's SD_{g95} such as

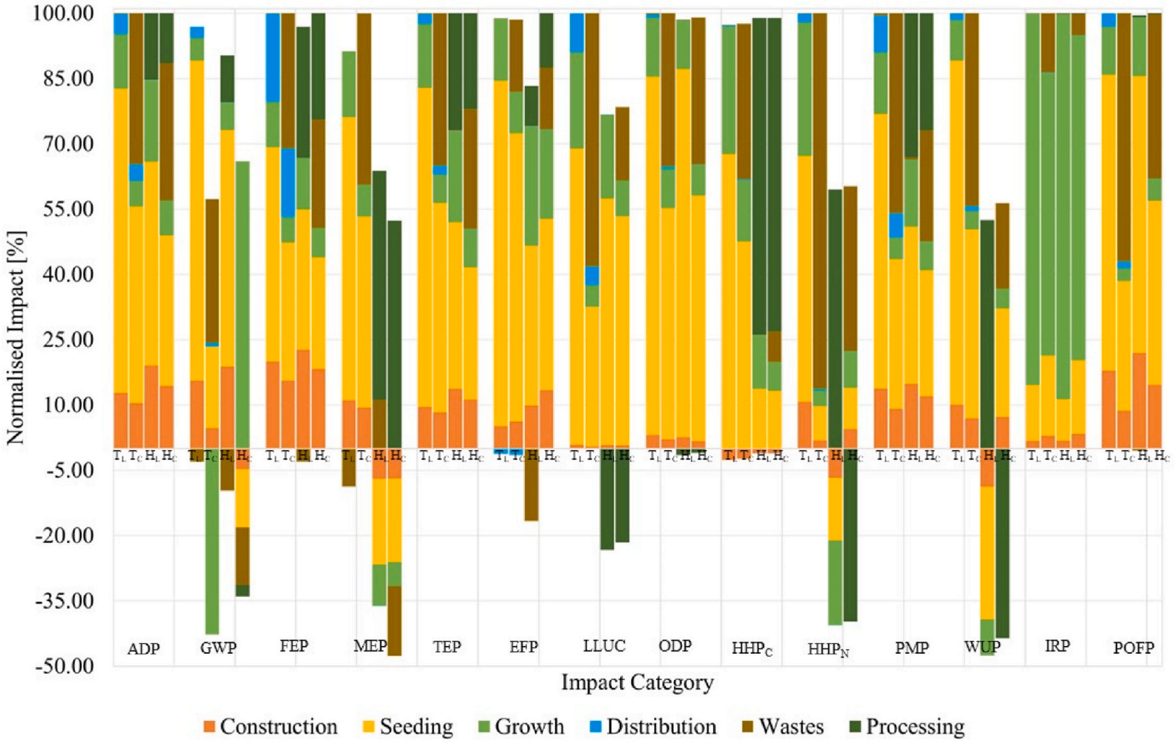

Fig. 3. Impact of environmental categories for each growth phase after 20 years. The scores of the crop's growths were normalised by their contribution to the impact category. The combined size of each phase is equal to 100 in all scenarios. Abbreviations are defined in SM.

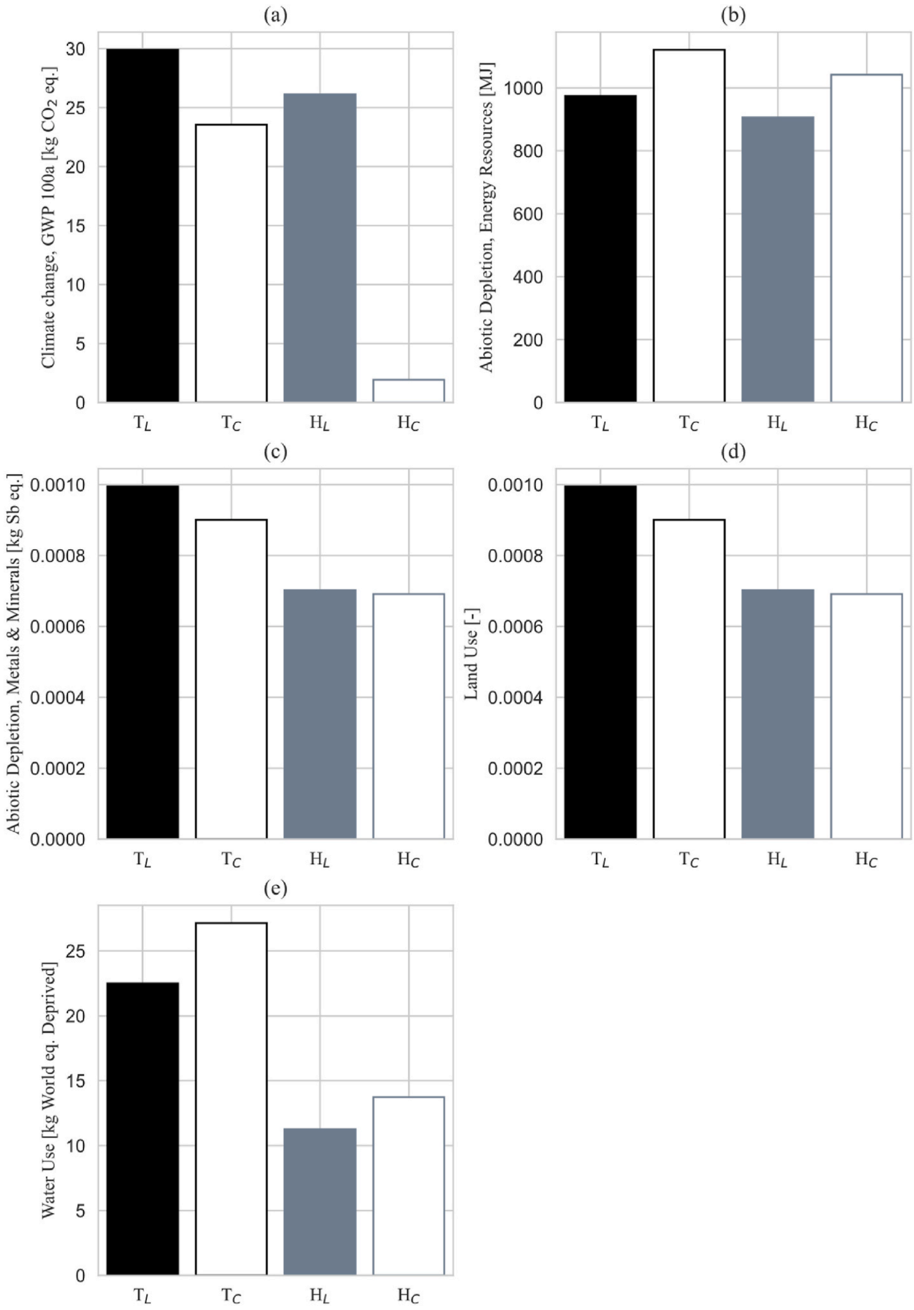

Fig. 4. Impacts after one year of crop growth in the glasshouse. (a) global warming potential with a 100-year time horizon, (b) abiotic depletion of energy resources, (c) abiotic depletion of metals and minerals, (d) dimensionless land use and land use change, (e) water use.

technological and temporal relevance.

Fig. 7 shows the first order sensitivity indices of the GWP for each scenario. The construction and growth phases were the most sensitive of the six phases. This was due to the relatively large amount of material requirements and their associated uncertainties in these phases compared to the others.

The introduction of circular practices has a reduction on the GWP, which is beneficial towards the goal of mitigating the effects of climate change. However, these practices also lead to greater depletion of water, energy resources and changes to land quality through the additional transformation activities required to recycle materials. Therefore, a transition to more circular manufacturing processes also requires the consideration of more than just the GWP to avoid causing more ecological issues while trying to solve one. To avoid these impacts the implementation of less energy intensive and more geographical availability of recycling processes is needed. Furthermore, expansion of LCA system boundaries in general may lead to clarity of which specific processes are leading to increased impacts of these highlighted impacts. Using the consequential LCA methodology rather than attributional LCA for prospective scenarios such as presented in this study along with a diverse range of impacts are required in future studies.

3.2. Techno-economic analysis

3.2.1. Circularity versus economics

The techno-economic analysis (TEA) showed that all scenarios were benefitted by the implementation of circular strategies, leading to higher NPV values than the linear systems. Fig. 8 summarizes the results. The potential of the economic feasibility for the scenarios was evaluated by plotting the NPV versus the cultivated area (Fig. 8-a). The analysis also

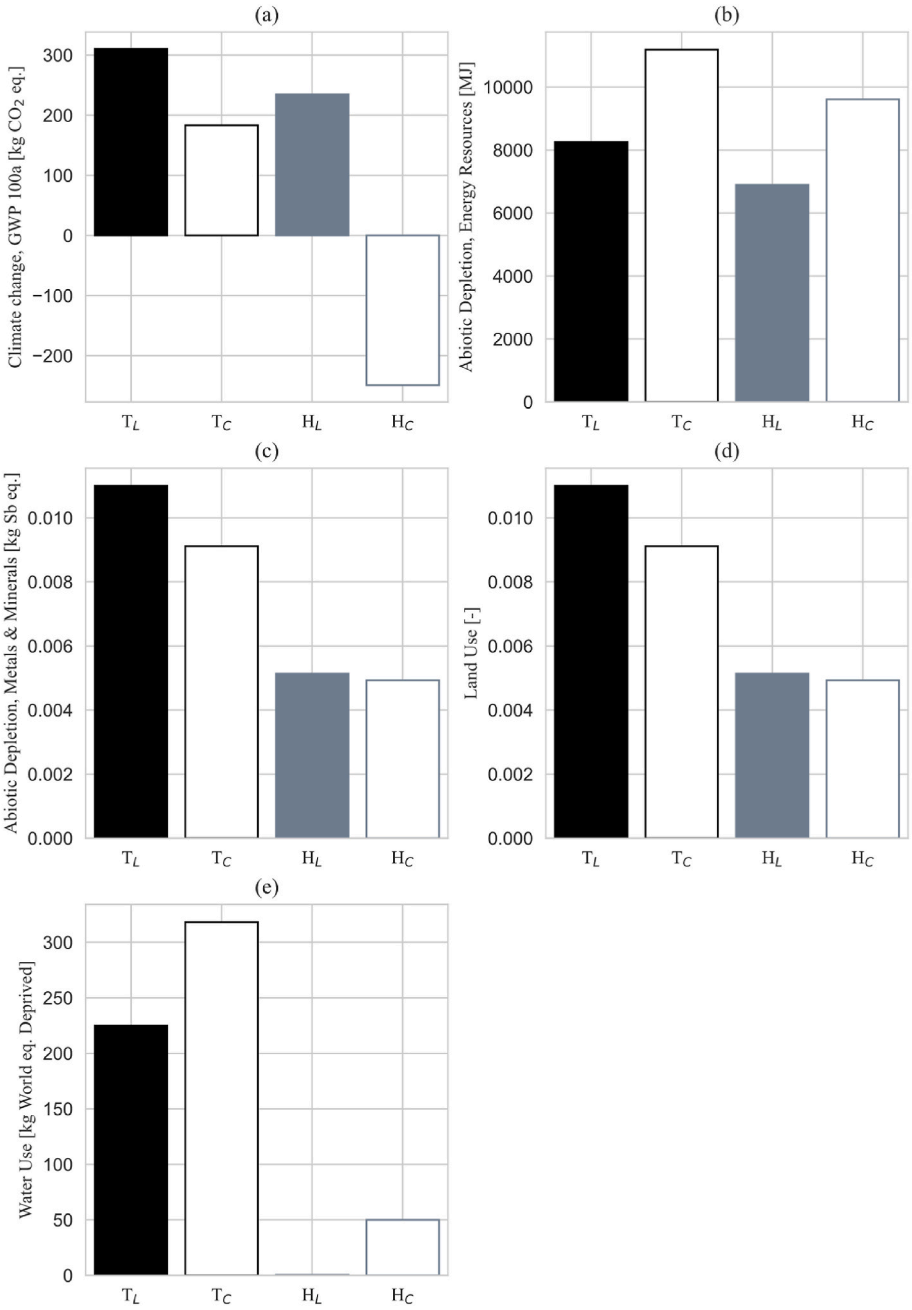

Fig. 5. Impacts after twenty years of crop growth in the glasshouse. (a) global warming potential with a 100-year time horizon, (b) abiotic depletion of energy resources, (c) abiotic depletion of metals and minerals, (d) dimensionless land use and land use change, (e) water use.

showed that the greater the planted area, the greater the system NPV for T_C, which was the unique profitable scenario under this study's conditions – full description available in Tables 1–4 Interestingly, the reduction of OpEx from hemp cultivation under circular circumstances was not enough to provide its profitability, which was still limited by the system's revenue – or product yields and their market price/demand. Additional techno-economic indicators (CapEx, OpEx, Product yield, CO_2 capture, and heat recovery) were evaluated for a fixed area (12,000 m^2), as shown in Fig. 8-b.

Clearly, the recovering of energy, CO_2, and fertilizers had a significantly impact on the scenario's economics by reducing by almost half the OpEx from linear to circular systems (Fig. 10-b). The recovery of the industrial streams enhanced the profitability of the tomatoes and almost provided a profitable system for H_C. H_C provided both highest CO_2 capture (~50 ton/y, reducing the OpEx by £98.5/year) and potential heat savings (15 MWh/y, reducing the OpEx by £1530/year). The recovered CO_2 and its savings were especially important for the development of a circular economy since this carbon source recovery/processing could be charged to the waste emitter as a waste treatment or commercialised as a commodity – as estimated for the linear systems (Tables 1 and 2). The CO_2 market could be uncertain, and the system feasibility could vary significantly. The influence of varying the CO_2 cost (£1.67 - £2.26/ton.) was combined with ±15% of variation on all inputs (OpEx) to evaluate the response on NPV and its uncertainty for different product's selling price (T_L; H_L), enhancing the robustness of the TEA estimation.

3.2.2. *Uncertainty and sensitivity analysis*

The productivity, capital (CapEx) and operational expenses (OpEx) were considered as the key-factors of the glasshouse profitability. Fig. 9-

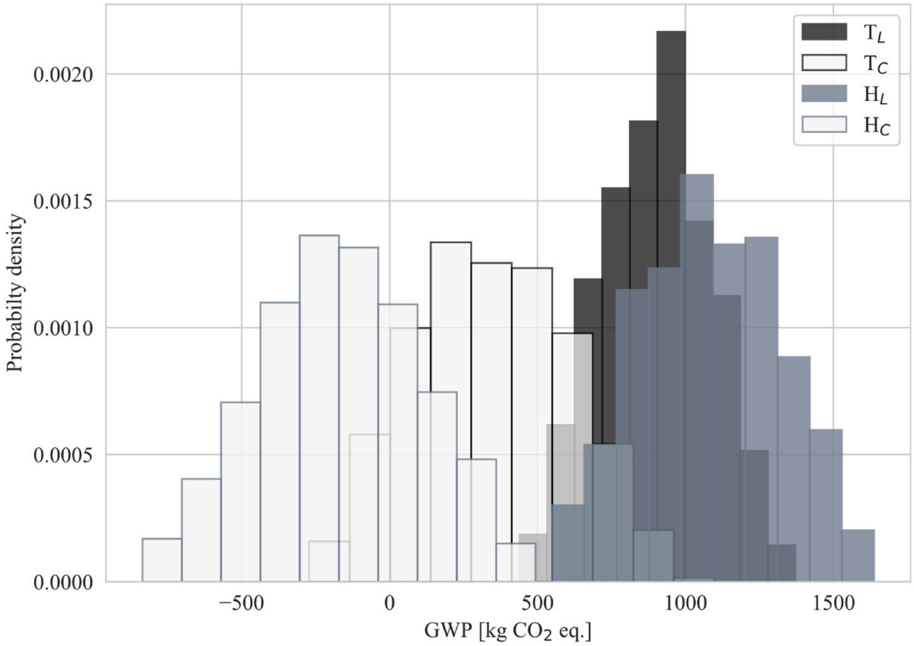

Fig. 6. Results of propagating input uncertainty to the GWP output for each scenario using Monte Carlo LCA where the inputs were varied by small, pseudo-random amounts.

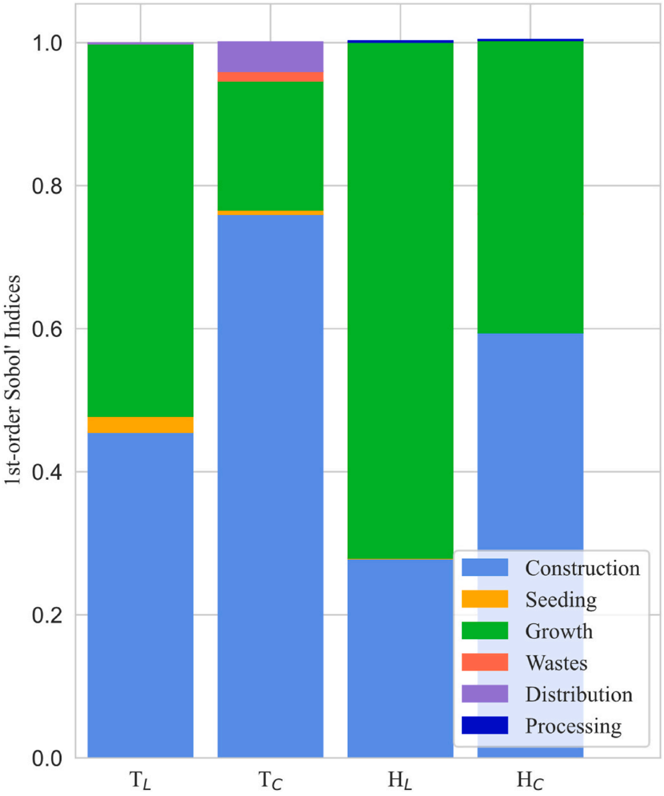

Fig. 7. First order sensitivity indices of global warming potential for each scenario along the whole life cycle of the glasshouse.

a, -b, -c, and -d show the variation of the selling price of the products and its impact on the NPV with their uncertainty for T_L, H_L, T_C, and H_C, respectively.

The reduction of the OpEx due to the circular approach benefited the tomatoes cultivation (T_C, Fig. 9-b and 9-a) by providing a profitable system (NPV>0). For the former scenario, the price of tomatoes could be reduced by half if the glasshouse operated with circular specifications (Fig. 9-b). This result can be remarkable for UK markets since approximately £1 million of fruits and vegetables were imported (HMRC, 2022) from countries such as Netherlands, Spain, Morocco, France, and Belgium (OEC, 2023).

The hemp scenarios also had shown an interesting response on the system profitability due to the increase on the product selling price. While an increase of almost 6 times in the seed and fibre prices was required to achieve H_L profitability (Fig. 9-b), an increase of around 3 times could be enough for the profitability under circular operational conditions (H_C, Fig. 9-d). Unlike the tomatoes, the hemp market in UK has not totally settled yet as it is a nascent industry. The *Home Office* recently stated (January 2021) its intention to establish a legal framework for consumer CBD products - which were derived primarily from the plant *Cannabis sativa* (ACMD, 2021). In this context, it was important to note that the price estimates for hemp modelled in this study would need to increase by a factor of three in the near future to provide an interesting opportunity for the UK's farming business. In addition to the seeds and fibre products, another potential strategy to valorise hemp cultivation on glasshouses could include the extraction of essential oil (Zheljazkov and Maggi, 2021). The pharmacological properties of cannabis essential oils (Al Ubeed et al., 2022) are also an opportunity of high-value market to be explored, especially on industrial sites where the infrastructure could be allocated to reduce costs and facilitate the extraction process. Although this might be of interest for future studies, the development of such strategies is still highly uncertain.

The sensitivity analysis of the OpEx on the economic feasibility for each scenario showed high influence of the growth phase, especially for linear strategies, while the revenue (or the crop efficiency) had driven the economics of both circular and linear approaches (Fig. 10). The circular strategy reduced the growth phase influence on the economic feasibility and led to more competitive product price than the first approach by avoiding costs related to water consumption, CO_2 requirement, and heat supply.

The comparison the linear and circular scenarios for the cultivation of tomatoes, T_L and T_C showed a decrease from 30% to 2% of growth costs within the implementation of circular strategies (Fig. 10-a and 10-b). The former reduction of the costs due to high circularity on the glasshouses led to expressive changes on the selling price of the

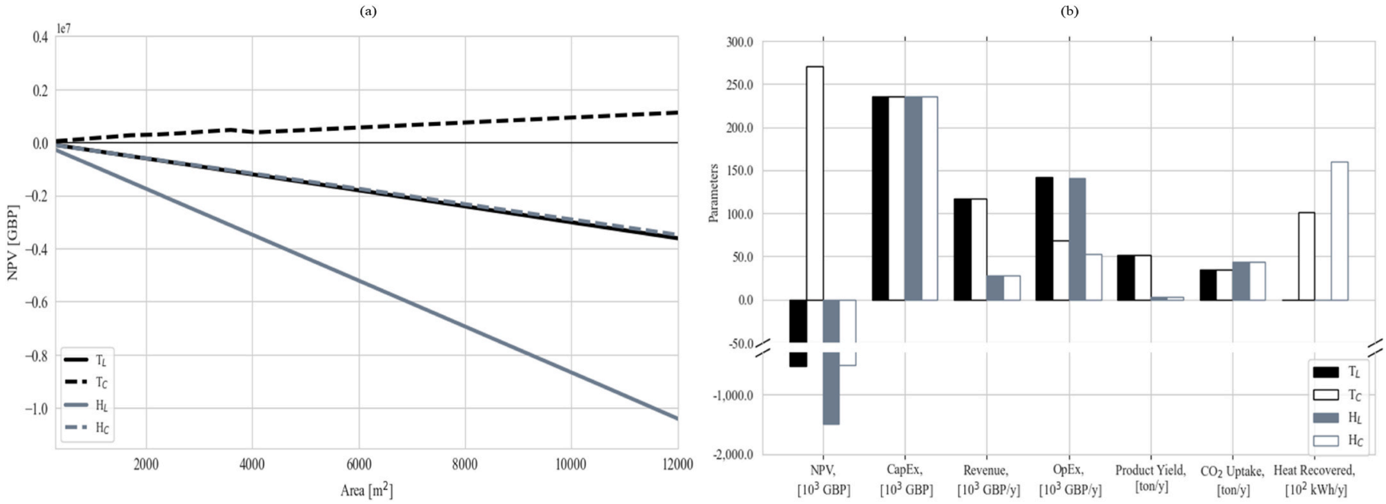

Fig. 8. TEA of glasshouses. (a) NPV as a function of the cultivation area. (b) Techno-economic analysis for 12,000 m^2 of planted area.

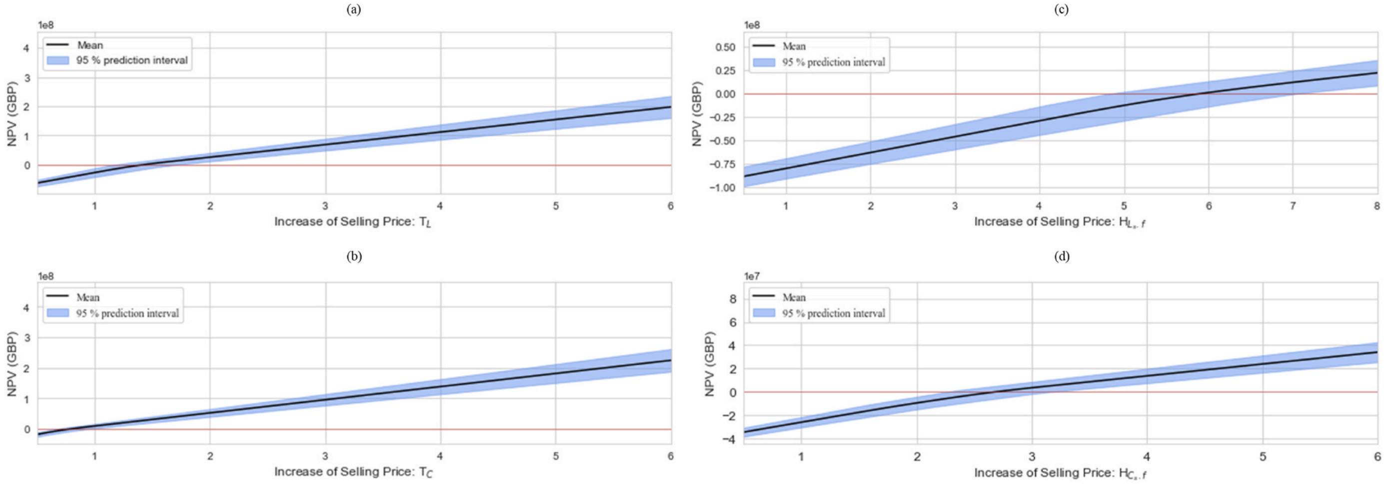

Fig. 9. TEA of the glasshouses.
NPV versus product selling price: (a)T_L; (b) H_L; (c) T_C; and (d) H_C. The uncertainty included ±15% of variation in products yields combined with ± 15% of costs changes (CapEx and OpEx) for each farming phase.

tomatoes, where the selling price of the tomatoes could be reduced by half – as in Fig. 9-a (T_L) and 9-b (T_C). On the T_C the economic feasibility was driven by the product yield, OpEx, and total project investment (TPI_{CapEx}) (Fig. 10-b), respectively. The T_L results were also explained by these key-parameters but with different proportionality representativeness (Fig. 10-a). Similar inferences were reported by Sanyé-Mengual et al. (2015), where the sensitivity assessment showed high influence of the product yields on tomatoes selling price. The study had also shown economic advantages from recovering residual energy - in this case, residual heat from offices.

Aligned with the tomato's cultivation, the growth phase was also the most expensive stage on the hemp cultivation, followed by other OpEx (Fig. 10-c and 10-d). For the circular scenario the decrease of the influence from the growth costs were observed, H_C (Fig. 10-c and 10-d). Other OpEx included legal and laboratory analysis, which justifies its higher representativeness for the hemp cultivation than for tomatoes since the former required expenses with THC analysis and licensing fees. Another peculiarity of the hemp farming was the high influence of the selling price of the seed (Fig. 10-c and 10-d) on the system profitability (NPV,Fig. 9-c and 9-d) due to its greater market-value than fibre.

3.3. Challenges of a circular economy

The crop growth within glasshouses could capture ~50 ton./y of CO_2 at commercial scale. The mitigation of GWP emissions were remarkable, but discussions around who should get the credit of the former benefits were still challenging when the recovery of the pollutants/wastes were performed for different stakeholders. The easy modelling of CCU could be done for the conventional LCA modelling, where the burdens remain to the polluter. However, additional waste streams could be shared by different systems, which become the main issue for allocating benefit/burdens as linear manufacturing moves toward the circular economy. The GWP emissions of the glasshouses operating under circular conditions, for instance, were also linked to other strategies and additional processing. Both recycling of plastics and the recovery of organic waste into biochar through its pyrolysis reduced the usage of raw materials. The potential environmental gain of reducing the energy demand was not evident for other impact categories since additional process for recycling and waste treatment in circular scenarios demanded extra resources. This was evident with the increase in energy resources, water use, and land use in circular scenarios.

Inclusion of different circular strategies led to complex system with recycling and reuse of resources. The system boundaries were expanded

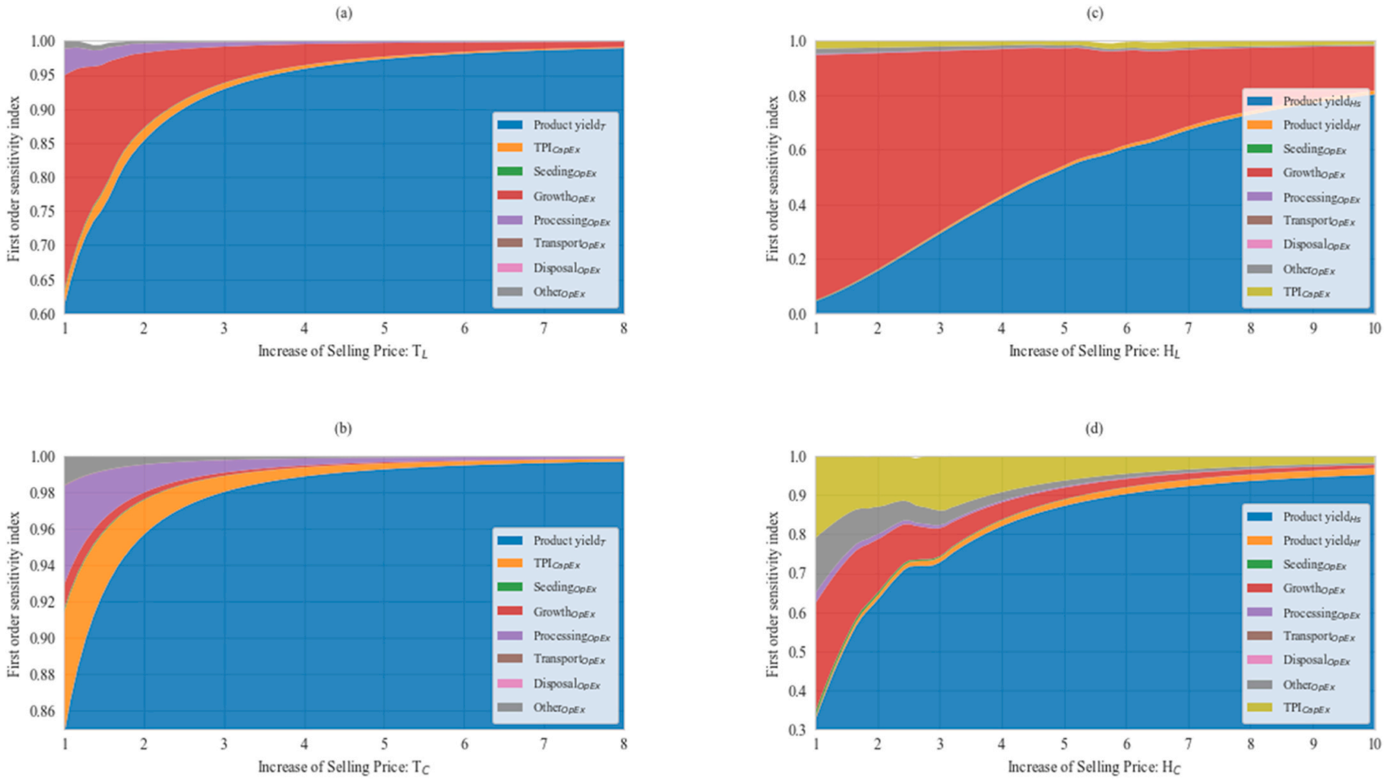

Fig. 10. Sensitivity analysis of the OpEx on the economic feasibility (NPV). Scenarios: (a) T_L; (b) T_C; (c) H_L; and (d) H_C.
The coloured area indicates the contribution of parameters on the system uncertainty, representing the proportional influence of each one on NPV uncertainty due to the increase of selling price.

to include strategies/processes for wastes management, for example. From a modelling perspective, the LCA became laborious and extra caution was required to avoid misleading conclusions that could occur due to double accounting of the potential impacts. However, in a circular economy, the connection among the processes is not under one exclusive business management, which could complicate the settlement of system boundaries and, consequently, could require shared environmental burdens/gains between stakeholders. The LCA modelling assumptions will either incentivise or disincentivise companies to use “waste” materials. Further work within LCA and carbon foot-printing methodological approaches are still desirable for a plausible division of the environmental impacts.

Glasshouses operating synergistically with the industry could be economically promising. The circular strategies could reduce the selling price up to half. The economic opportunity of reducing the importation of tomatoes should also be highlighted for the potential enhancement of the UK’s economy by bolstering domestic crop production. In 2016, UK imported from Spain and Netherlands 36 and 37% of its fresh tomatoes, respectively. The total greenhouse gas emission on UK’s supply chain was ~525,000 ton. of CO_2. In this context, the GWP emissions of the glasshouses could be negative in 20 years for tomatoes cultivation if the avoided emissions of shipping were discounted from the circular scenario, leading to −1.55 t of $CO_{2eq.}$ instead of ~0.150 t of $CO_{2eq.}$, if shipping emissions were offset by 1.68 ton. of $CO_{2eq.}$ (Xue et al., 2020).

4. Limitations and perspectives

The best- and worst-case scenarios for both tomatoes and hemp were evaluated to show that glasshouses could support a circular economy and its performance will depend on the crop selection and real-world climate and geographical conditions. In fact, different circumstances might be evaluated before investing. Future research involving pilot scale experimental results under the considered operating conditions should be used to validate the outcomes of this study.

The operation of the glasshouse in different regions could lead to practical implications when recycling and waste disposal facilities are evaluated. Although temporal paybacks of delaying carbon release into the atmosphere for fibre-products was not considered, the key-aspects to enhance crops productivity by recovering agro-industrial flows in a controlled system of glasshouses were identified. Considering the time horizon of 20 years (glasshouse lifespan) and the fast capture and release of carbon for 1 m^2 of glasshouse, the average values from linear and circular scenarios provided a realistic estimate of the environmental impacts. To evaluate the application of glasshouses as a mechanism for industrial CO_2 capture, the function unit was the cultivated area and additional manufacturing processes for hemp fibre were neglected. By using a cradle-to-grave approach for the products life cycle, further environmental benefits for cultivating hemp could be achieved, as were shown by Shen et al. (2022). Dynamic inventories, characterisation factors or inclusion of additional temporal aspects could also enhance the LCA accuracy in dynamic modelling (Cardellini et al., 2018; Pigné et al., 2019).

5. Conclusions

Creating synergistic mechanisms for enabling circularity between industry and agriculture could be critical for achieving a sustainable production of crops. Using one industrial “waste” as a resource for another business can be a potential strategy for mitigating the use of raw resources. However, to date, the impacts are still not clearly measured, and the complex system boundaries of circular systems gives rise to practical and methodological problems. A combined TEA and LCA with SA and UA approach was used to forecast profitable and sustainable operational conditions of recovering industrial wastes in a case study of crop growth on glasshouses. This circular strategy reduced the overall environmental impacts, mainly for the GWP that was reduced by ~110 kg $CO_{2eq.}$ for tomatoes and ~500 kg $CO_{2eq.}$ for hemp cultivation per 1 m^2 of glasshouse after a lifespan of 20 years. Circular assumptions-such as the use on rainwater in the system instead of tap water and reduction of fertilisers inputs – mitigated the use of raw inputs, avoiding the overall CO_{2eq} emissions. For the GWP, the growth phase exhibited the largest change between the linear and circular scenarios. Nevertheless, there were risks of some adverse impacts, on factors such as resource depletion, which shows that the seemingly intuitive view of a circular approach reducing impact is not always true. Cultivating crops with high biomass-content and low generation of biomass waste, such as hemp, can result in even greater environmental performance, due to savings on raw materials utilisation and energy requirement for disposing the harvesting wastes.

Critical to current food supply and security issues, the results showed that when industrial CO_2 and other circular strategies were employed, food products produced within glasshouses could be sold for up to half of their regular cost and remain profitable. This outstanding result can promote future investments on recovering wastes in glasshouses by increasing hemp and tomatoes production. For tomatoes, this could represent negative CO_{2eq} emissions by avoiding their importation from overseas. The main drivers of linear scenarios feasibility were the product yields, OpEx from growth stage, and total project investments. The SA had shown that the circular strategy can reduce the growth phase influence on NPV up to 28% (T_C) and led to more competitive product's price than the first approach due to savings on water, CO_2, and heat consumption. The representativeness of CapEx on NPV increased due to the mitigation of OpEx when circular strategies were applied. Expenses with THC analysis and licensing fees were also representative for hemp, mainly for H_C.

Indeed, industries and farmers should work together to provide multiple impacts of resource security, environmental improvement, and wider financial benefit. However, current working practices do not incentivise this wider system thinking. This research delivers critical information about circular methods and impact calculation, through the use of the industrial case study. The methodology that was proposed and used should support the implementation of a circular economy.

CRediT authorship contribution statement

Lewis J. McDonald: contributed equally to design the study, carried out the process simulations for techno-economic-environmental assessments and manuscript preparation. **Ariane S.S. Pinto:** contributed equally to design the study, carried out the process simulations for techno-economic-environmental assessments and manuscript preparation. **Muhammad Naveed Arshad:** provided critical data, feedback and contributed to final version. **Rebecca L. Rowe:** Funding acquisition, provided funding acquisition and coordinated the study. **Iain Donnison:** Funding acquisition, provided funding acquisition and coordinated the study. **Marcelle McManus:** Funding acquisition, provided funding acquisition and coordinated the study, All authors analysed the results and provided a critical review of the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors would like to thank Industrial Decarbonisation Research and Innovation Centre (IDRIC-UKRI [grant number: EP/V027050/1]) and Supergen Bioenergy Hub 2018 [grant number: EP/S000771/1] for providing necessary resources.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139650.

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