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Title Page:

Human-powered hydroponic systems: An environmental and economic assessment

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Abstract:

Hydroponic systems like vertical farming have been proposed as an alternative and potentially more sustainable option for growing vegetables than conventional soil-based production methods. However, the energy required for the functioning of hydroponic systems is a key contributor to the total environmental impact and economic cost. Human-powered hydroponic systems, which utilise human muscular exertion to power the system, have not been thoroughly investigated, despite their potential as a cost-efficient and less harmful alternative to the environment. This paper presents a prototype of a novel human-powered hydroponic system and assesses its environmental impact and economic costs using life cycle assessment (LCA) and life cycle costing (LCC), considering the cultivation of lettuce as a case study. A scenario analysis was performed to assess the environmental impact of lettuce production using a human-powered hydroponic system compared to conventional soil or greenhouse-based production methods. Using SimaPro LCA software, 18 impact categories included in the ReciPe Midpoint (H) method were evaluated. The results indicated that the battery, followed by the power system, represented the primary environmental hotspots of the human-powered hydroponic system. Improving the yield (production of 6 lettuces of 500 g vs 200 g per 40-day growing cycle) of the human-powered hydroponic system can reduce the environmental impact of lettuce production compared to conventionally soil-based produced lettuce in 11 out of the 18 evaluated impact categories, and when compared to greenhouse-produced lettuce, it generates lower impacts in 14 out of 18 categories. Regarding economic cost, considering a yield of 1.2 kg (6 lettuces of 200 g) per 40-day growing cycle with the human-powered hydroponic system, it is more expensive for the consumer than buying lettuce produced with conventional soil-based open-field agriculture and greenhouses, and break-even points are not achievable within 15 years (the lifespan of the system). However, when considering a yield of 3 kg (6 lettuces of 500 g), the break-even point with greenhouse-produced lettuce was achieved between 10 and 11 years. Therefore, although a break-even point is not achievable within the considered lifespan of the developed system, it could be reached if the yield of the system increased and/or if the system had a longer lifespan, which is mainly determined by the lifespan of the battery.

Keywords: Human-powered hydroponic systems; vertical farming; life cycle assessment (LCA); life cycle costing (LCC); hydroponics; urban agriculture.

1. Introduction

Conventional agricultural practices in both open-field and greenhouse settings require soil as a medium for cultivating crops. However, the effectiveness of these soil-based methods has been debated. Previous studies (Barbosa et al., 2015; Khan et al., 2018) have indicated that these methods may not be the most effective in terms of yield, which will be a key requirement for agricultural methods in the future, in light of the rapidly growing population whose demand for fresh produce in cities is growing exponentially (Gentry, 2019; Croce and Vettorato, 2021). In addition, these conventional methods present other disadvantages such as the requirement for abundant fertile land (Dholwani et al., 2018) or specific weather and geographical conditions to grow certain crop varieties (Barbosa et al., 2015). These methods are also water and labour-intensive, prone to infestations (Khan et al., 2018), and require the use of pesticides to avoid and control plagues.

New, potentially more effective agricultural techniques have emerged as viable alternatives to conventional soil-based practices. Hydroponics is one such alternative. Compared with soil-based agricultural methods, hydroponics has many benefits (Barbosa et al., 2015; Khan et al., 2018; Sebring et al., 2022) such as i) longer growing seasons (Brechner and Both, 2013), ii) less use of water, pesticides, and soil degradation; and iii) faster crop growth and higher yields (Dholwani et al., 2018). Hydroponics only requires water and nutrients dissolved in the water to feed plants. Currently, there are many commercially available hydroponic systems for indoor and outdoor use and domestic or commercial applications. However, (Nisha et al., 2019) stated that hydroponic systems used for commercial applications (e.g. vertical farms) have a high initial manufacturing cost, representing one of the key barriers to wider deployment, particularly for those designed for indoor use (e.g. greenhouse vertical farming) in cold and dark climates (i.e. higher-latitude countries). Moreover, most current hydroponic systems rely on the power grid to function, except for some exceptions in which hydroponic systems are powered by photovoltaic (PV) systems (Xu et al., 2022) or hybrid renewable energy systems (Udovichenko et al., 2021). Barbosa et al. (2015) also mentioned the high power consumption required to operate these systems, mainly from heating and cooling loads and artificial lighting, which are the main contributors to their negative environmental impacts. The same study suggested that if these systems were powered using alternative (renewable) sources of energy that do not rely on fossil fuels, hydroponic systems could potentially be a very effective and sustainable option for growing crops.

Assessing the long-term sustainability and economic feasibility of these technologies is key to assessing their benefits and areas for improvement before widespread adoption; hence, previous research has focused on gaining an understanding of their environmental impact (e.g. Blom et al. 2022; Ghasemi-Mobtaker et al., 2022; Pinho et al., 2022), economic cost (Udovichenko et al., 2021; Gumisiriza et al., 2022), and the feasibility of replacing grid power with renewable energy sources (Ronay and Dumitru, 2015). However, the environmental impact assessments conducted in these studies did not always consider all the environmental impact categories. For example, some studies have focused solely on analysing the carbon footprint (Ntinas et al., 2020; Casey et al., 2022) and were typically developed for commercial applications rather than residential use (e.g. Urbano et al., 2022). The findings of previous studies also suggested that the energy necessary to cool and heat greenhouses where hydroponics are employed has the greatest environmental impact (Romeo et al., 2018; Chen et al., 2020). Barbosa (2015) further mentioned that less complex (with fewer electrical-electronic systems involved) hydroponic systems could demand significantly less energy, making them more sustainable, given that the use phase of hydroponic systems is the primary cause of their total environmental impact. However, this may not apply to domestic-oriented hydroponic systems because the type of hydroponic system required may be less costly to manufacture, maintain, and run. Domestic hydroponic systems with lower power use may not encounter the same challenges as those encountered in previous studies of hydroponic systems. Furthermore, if the electrical power of such a system can be generated from renewable energy sources, it could potentially be even more sustainable and economically efficient. Human power can be suggested as an alternative energy source, where the exertion of human muscle energy (i.e. mechanical power) can be converted into electrical power to operate hydroponic systems, such as a pedal-powered generator. However, there is a lack of published research assessing and analysing the viability of human power as an alternative energy source to power hydroponic systems.

This paper presents a novel human-powered hydroponic system developed by the authors and an assessment of its environmental impact and economic cost. To the best of our knowledge, hydroponic systems powered by humans have not been developed or manufactured to date, despite presenting a potentially more sustainable and cost-effective alternative to existing hydroponic systems, considering that they do not require energy from the grid to function, resulting in reduced environmental impact and cost.

This paper first presents a literature review, followed by the methodology to assess the environmental (LCA: Life Cycle Assessment) and economic (LCC: Life Cycle Cost Analysis) impacts of the developed human-powered hydroponic systems, followed by the results and discussion, including sensitivity and scenario analysis, and conclusions. Further details regarding the assessed human-powered hydroponic system are provided in the Appendix.

2. Literature review

The literature review is divided into two sections: previous studies that assess the environmental impact of hydroponic systems, and studies that assess their economic cost.

2.1 Environmental impact of hydroponic systems

Several studies (Appendix, Table 1) have assessed the environmental impacts of hydroponics systems and other agricultural systems. Pinho et al. (2022) compared hydroponic systems with FLOCponics and biofloc systems using emergy synthesis, finding that biofloc systems had the lowest environmental impact, followed by FLOCponics and hydroponic systems. However, the hydroponic systems evaluated in this study were powered by grid electricity, rather than human power. Additionally, the environmental impact assessment utilised emergy synthesis instead of life cycle assessment (LCA). In another study, Ghasemi-Mobtaker et al. (2022) conducted an LCA to analyse the environmental impact of hydroponic systems in fodder production. They identified seed production, energy use during the operational phase, and fertiliser production as the key factors contributing to the total environmental impact of hydroponic systems. These findings suggest the need to optimise energy utilisation and explore renewable energy sources to reduce the environmental footprint of hydroponic systems. The hydroponic systems evaluated in both studies were powered by grid electricity and natural gas within commercial greenhouses rather than in domestic vertical farming-like settings.

Blom et al. (2022) compared the carbon footprints of different agricultural systems, including hydroponic systems, finding that vertical farming hydroponic systems (VFHS) have a significantly higher carbon footprint than soil-based open-field farms, soil-based greenhouses, and hydroponic greenhouses. Electricity consumption during the use phase was identified as the primary contributor to the carbon footprint of VFHSs. Despite the use of PV panels, grid electricity accounted for most of the carbon footprint. Romeo et al. (2018) assessed and compared the environmental impacts of a VFHS, soil-based greenhouse, and on-field cultivation using an attributional cradle-to-gate LCA. The results showed that VFHS could deliver higher yields and had an environmental impact comparable to that of on-field cultivation, which was 2 to 12 times lower than soil-based heated greenhouse production in a heated greenhouse.

Other studies (Rothwell et al., 2016; Chen et al., 2020; Ntinas et al., 2020; Udovichenko et al., 2021; Casey et al., 2022; Urbano et al., 2022) have assessed and compared the environmental impact of hydroponic systems and other agricultural methods. These studies consistently highlight power use, energy sources, and greenhouse-gas-related emissions as significant contributors to the total environmental impact. Although some hydroponic systems utilise renewable energy sources, most rely on grid electricity and are primarily designed for commercial rather than residential applications. The results of these studies highlight the importance of optimising resource inputs, minimising energy usage, and investigating renewable energy sources to reduce the negative environmental impacts of hydroponic systems. Overall, these studies suggest that hydroponic systems have the potential to contribute to more sustainable and efficient agricultural systems. However, careful attention must be paid to their design, operation, and energy sources to reduce their environmental impact.

Based on the literature review, it can be concluded that the environmental impact of hydroponic systems has been assessed in several studies (Appendix, Table 1). However, none of the hydroponic systems assessed in these studies were human-powered, and a significant proportion of the non-grid-powered hydroponic systems relied on non-renewable or hybrid energy sources. Furthermore, the environmental impact assessments conducted in these studies did not always consider all environmental impact categories; they typically focused solely on analysing the carbon footprint and were developed for commercial rather than residential use. These studies also demonstrated that the energy required to cool and heat greenhouses in which hydroponics were employed had the greatest environmental impact.

2.2 Economic assessment of hydroponic systems

Several studies (see Appendix, Table 2) have assessed the economic costs of different hydroponic system types. Gumisiriza et al. (2022) performed a cost-benefit analysis of non-greenhouse hydroponic systems using the following methods: Net Present Value (NPV), Profitability Index (PI), Internal Rate of Return (IRR), and Non-Discounted Payback Period (NDPBP). The results of this study showed that the hydroponic system was cost-effective. However, the hydroponic systems in this study did not require energy from the grid to be powered, and the type of hydroponic system used was very different from that used in the present study, which was based on a continuous circulating flow solution. The assessed hydroponic systems did not require costly equipment such as water pumps, which can significantly reduce the total life cost compared with the human-powered hydroponic systems developed in this study. In addition, the hydroponic systems developed in this study are for indoor domestic use applications that benefit from the internal environmental conditions inside the house and are designed to produce lower yields requires systems with lower complexity. Udovichenko et al. (2021) assessed and compared the costs of production and transport (import) of lettuce using conventional soil-based methods at warmer latitudes with the production of lettuce using hybrid renewable-energy-powered-assisted hydroponic systems for indoor applications in northern Canada. Hydroponic systems were assessed by retrofitting an existing building to create a commercial hydroponic farm in northern Canada. The results showed that lettuce production using hydroponic systems had a lower economic impact than lettuce production using conventional soil-based methods. The cost assessment of this hydroponic system differs from that of this study because it was used for industrial purposes, powered by renewable (e.g. solar) and non-renewable energy sources, and focused on one environmental impact category (GWP: Global Warming Potential). Nisha et al. (2019) also mentioned that hydroponic systems used for commercial applications (e.g. vertical farms) have a high initial manufacturing cost, representing one of the key barriers to wider deployment. In general, all previous studies suggest that the use phase of the hydroponic system life cycle is usually the life cycle with the highest environmental impact, which means that the energy source used to power hydroponic systems is very important for reducing the total environmental impact of hydroponic systems.

Thus, it can be concluded that there are no published studies on the environmental and cost-related impacts of human-powered hydroponic systems. However, the review identified environmental and/or cost impact assessment studies (Appendix, Tables 1 and 2) that used various methodologies to assess other types of nonhuman-powered hydroponic systems powered by different energy sources. These findings provide insights into the methodology used in this study to assess the environmental and cost impacts of human-powered hydroponic systems and to identify the higher environmental and cost impact areas of existing hydroponic systems. The identified areas should also be addressed in the design and manufacturing of future hydroponic systems to reduce their environmental impact and costs.

2. Methods

The methodology applied in this study is based on the application of two assessment methods, life cycle assessment (LCA) and life cycle costing (LCC), to assess the environmental impact and economic cost of a human-powered hydroponic system life cycle, respectively. The LCA was conducted using the following steps: 1) goal and scope definition, 2) life cycle inventory (LCI), 3) sensitivity analysis, 4) scenario analysis, and 5) life cycle impact assessment (LCIA) method selection. The LCC was conducted by the following steps: 1) goal and scope definition, 2) life cycle inventory, and 3) economic assessment method selection, which included the following cost categories: costs to a) acquire (acquisition cost), b) operate (operating cost), and c) maintain (maintenance, repair, and replacement costs) the human-powered hydroponic system. Steps 1 and 2 of the LCA selected the same parameters; therefore, both models (the environmental impact and cost models) considered the same assumptions.

2.1 Life Cycle Assessment (LCA)

2.1.1 Goal and Scope

The aim of this LCA study was to analyse the environmental impact of a novel human-powered hydroponic system (Figure 1) prototype developed by the authors to understand its environmental impact and identify opportunities to reduce it.

Lettuce was selected as the functional unit in this study based on a comprehensive review of hydroponic research. Lettuce is widely regarded as an ideal model crop for investigating the effects of artificial lighting on vertical farming because of its rapid growth and short production cycles (Voutsinos et al., 2021). The functional unit selected was 1 kg of lettuce produced in a human-powered hydroponic system every 40 days, with a system lifespan of 15 years. The 40-day growing cycle was selected based on the lettuce harvest cycle using this system. The system boundaries considered in this assessment are illustrated in Fig. 2. The LCA adopts a cradle-to-consumer approach (i.e. the system boundaries include all activities from the extraction of resources used to fabricate the human-powered hydroponic system to the point where the lettuce is harvested at home). End-of-life was not considered because it was not a life-cycle stage of the system we wanted to assess in this study. Therefore, this study focused only on the manufacturing and use life cycle stages.

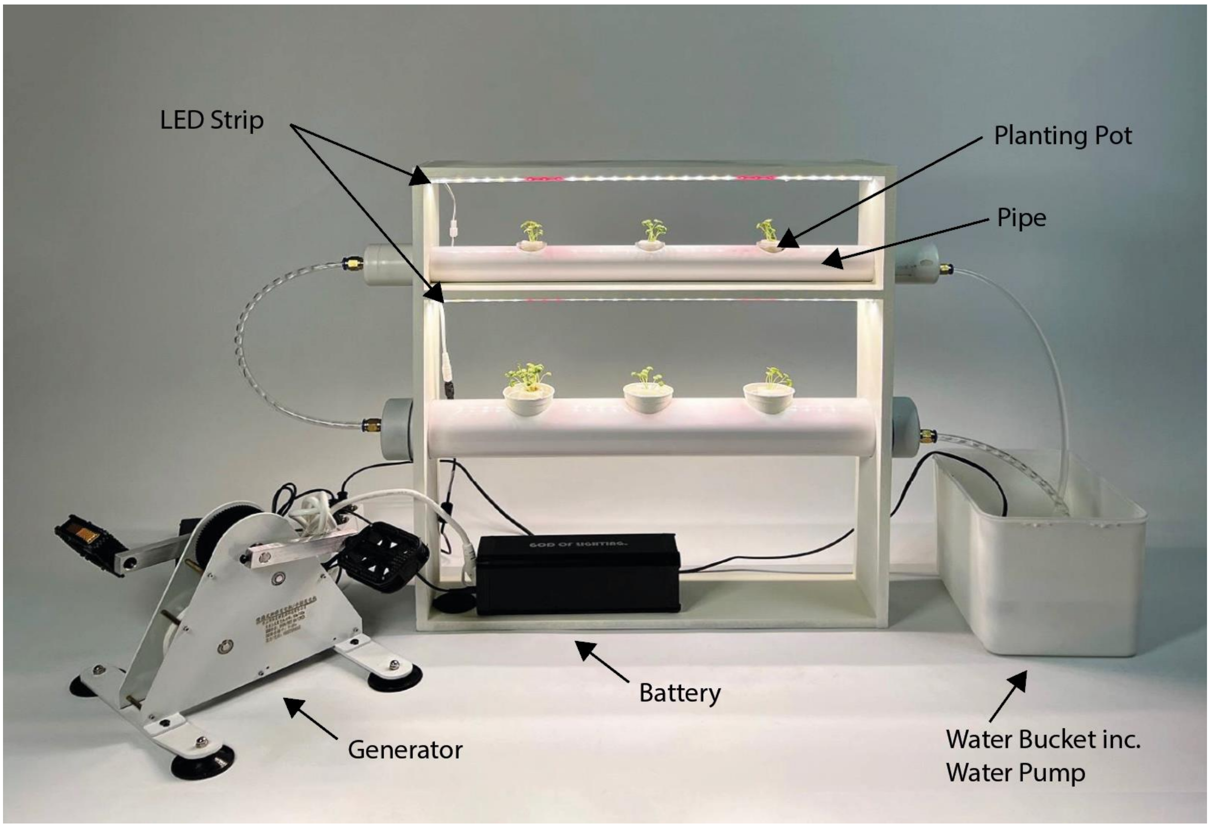


Figure 1. Prototype of the human-powered hydroponic system.

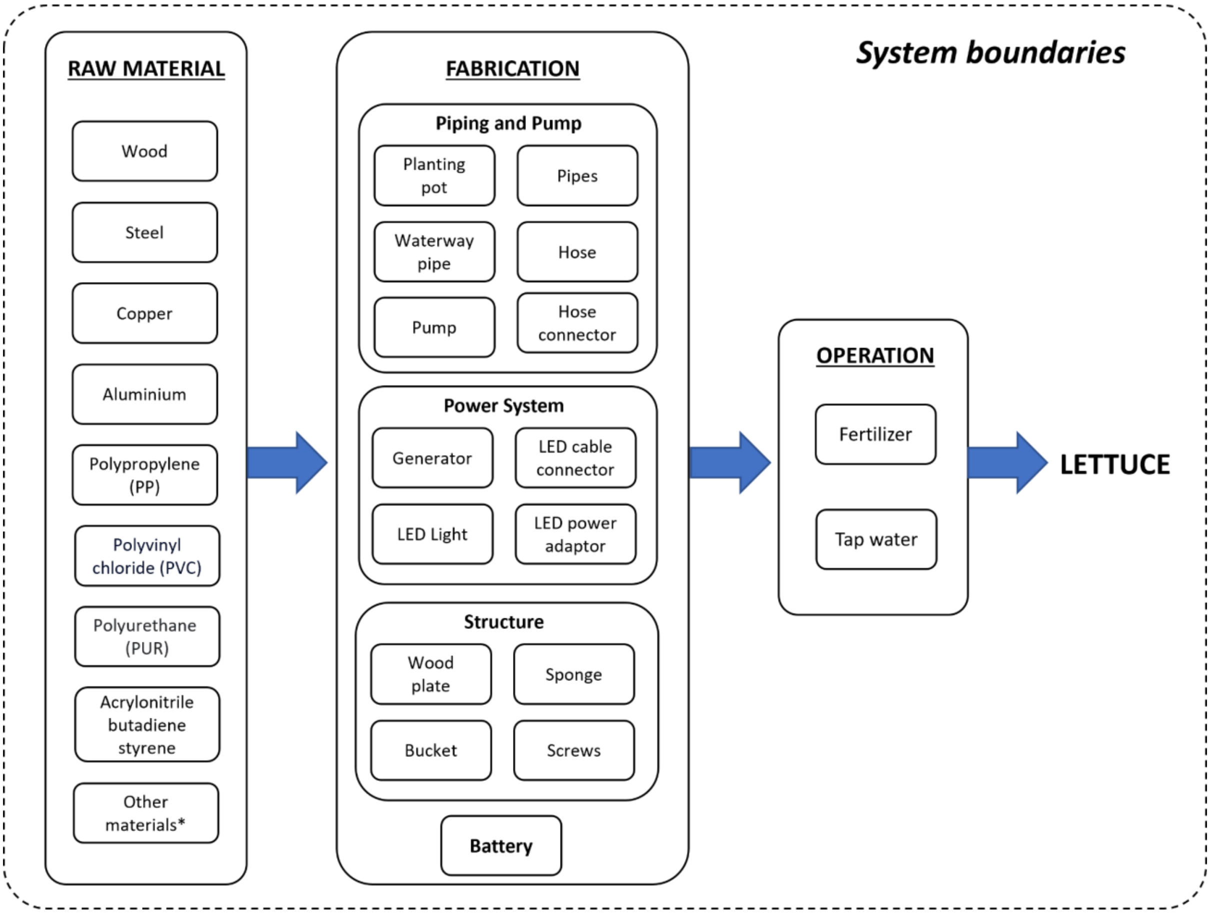


Figure 2. System boundaries of the LCA.
LED: light-emitting diode. ** Other raw materials encompass all materials utilised in component manufacturing but are not inherently integrated into the system, such as natural gas, crude oil, coal, and other substances.*

2.1.2 Life Cycle Inventory (LCI)

The LCI data associated with the human-powered hydroponic system fabrication are listed in Table 1. The battery lifespan was determined based on the maximum charge-discharge cycles reported in the technical datasheet of the battery (PowerTech Systems, 2023). To estimate the maximum number of charge/discharge cycles of the system, it was necessary to determine its energy consumption. The system uses 90 units of 0.05 W LED, which are turned on 20 h per day. Based on this assumption, the energy demand for lighting is 0.09 kWh/day. The water pump uses 3 W and is operational 24 h a day, resulting in an energy consumption of 0.072 kWh/day. Consequently, the total energy consumption of the human-powered hydroponic system is 0.162 kWh/d which is equivalent to the energy generated from pedalling the ‘generator’ for 1.5 h (Figure 1). The amount of power generated by people using the generator per day or week may vary depending on the amount pedalled each day or week. However, in this study, we assumed that the battery must have the capacity to store energy to meet the system requirements for at least two days when energy is not being produced from the generator. Therefore, the battery must have a storage capacity greater than 0.324 kWh. Based on this assumption, a 12V, 30Ah lithium battery was selected with a storage capacity of 0.384 kWh, guaranteeing 3,000 charge cycles with 100% efficiency. Considering three weekly charges and 15 years of lifespan, 2,340 useful lifecycles were assumed. The battery lifespan assumption was based on the battery manufacturer’s technical datasheets, which state a lifespan of > 10 years and on a previously published study (Kritzer and Nahrwold, 2019), which indicated that a lithium battery can last up to 15 years.

Table 1. Life cycle inventory of the human-powered hydroponic system.

	Material	Unit	Part weight	Quantity	Total weight
Piping and pump					
Small white planting pot	PP	g	1.5	6	9.0
Hose-pipe connector	ABS	g	2.0	1	2.0
Pipe (60 cm)	PVC	g	845.1	2	1690.2
Hose (large)	PUR	g	11.8	2	23.6
Pipe cap (black)	PVC	g	22.7	4	90.8
Hose connector	PVC	g	10.0	4	40.0
	Brass	g	10.0	4	40.0

Pump	Aluminium	g	1.5	1	1.5
	Cast iron	g	92.9	1	92.9
	Copper	g	19.4	1	19.4
	PVC	g	2.3	1	2.3
	Chromium steel	g	71.2	1	71.2
	Rubber	g	0.5	1	0.5
Power system					
Generator	Screw (steel)	g	2.1	4	8.4
	Screw (steel)	g	3.8	3	11.4
	Screw (steel)	g	2.1	4	8.4
	Screw (steel)	g	0.6	16	9.6
	Screw (steel)	g	1.6	3	4.8
	Hollow screw (ABS)	g	0.2	5	1.0
	Hollow screw (brass)	g	4.1	7	28.7
	Bar (steel)	g	76.7	1	76.7
	Bar (steel)	g	30.0	1	30.0
	Gears (steel)	g	505.3	1	505.3
	Other parts (steel)	g	2336.4	1	2336.4
	Pedal (ABS)	g	97.1	2	194.2
	Rubber parts	g	77.2	1	77.2
LED Light	LED	g	57.8	3	173.4

LED cable connector		g	4.4	3	13.2
LED power adaptor		g	252.2	3	756.6
Battery Lithium 12V 30Ah	Battery materials	g	3440	1	3440
Structure					
Wood plate	MDF	g	382.0	5	1910.0
Sponge (large)	PUR	g	0.6	30	18.0
Bucket	PP	g	425.5	1	425.5
Screws	Aluminium	g	2.6	14	36.4

LED: Light-emitting diode. MDF: Medium-density fibreboard. PP: Polypropylene. ABS: Acrylonitrile butadiene styrene. PVC: Polyvinyl chloride. PUR: Polyurethane.

The quantity and quality of fertilisers used during the operation of the system were determined based on the nutrient requirements of the human-powered hydroponic system (Table 2). The fertilisers were diluted in 12 litres of water and recirculated using a water pump.

Regarding the production of the human-powered hydroponic system, six lettuces of 200 g each are produced in a 40-day cycle. Throughout the lifespan of the human-powered hydroponic system (15 years), 136.9 cycles are conducted, producing 164.25 kg of lettuce. The lifespan of the human-powered hydroponic system was determined based on the lifespan of the battery, which was the component most likely to fail first.

Table 2. Nutrient requirements and fertilisers per each cycle of the human-powered hydroponic system.

	Unit	**Amount**	**N**	**P**	**K**	**Ca**
Requirements nutrient	g/cycle		**0.79**	**0.36**	**2.04**	**0.48**
Fertiliser			**Nutrients**			
NPK	g/cycle	2.40	0.36	0.36	0.36	-
Calcium ammonium nitrate	g/cycle	1.45	0.39	-	-	0.48
Inorganic potassium	g/cycle	2.02	-	-	1.68	-
Urea	g/cycle	0.09	0.039	-	-	-

Amounts indicated in the table are g/40-day cycle.

2.1.3 Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of increased lettuce productivity (yield) on the total environmental impact of the human-powered hydroponic system. A gradual increase in the average weight of each lettuce produced was evaluated, ranging from 200 to 500 g. This range was deemed potentially feasible based on the findings of Ezziddine et al. (2021). As the average weight of the lettuce increased, the fertiliser requirements also increased proportionally. The fertiliser increment was estimated based on the percentage relationship between the initial average weight (200 g) and evaluated increments of 250, 300, 350, 400, 450, and 500 g.

2.1.4 Scenario analysis

A scenario analysis was conducted to compare the environmental impact of lettuce produced using the human-powered hydroponic system with that of lettuce produced using conventional soil and greenhouse-based agriculture methods. Four scenarios were modelled for this purpose. Scenario 0 represented the human-powered hydroponic system model with a production of an average lettuce weight of 200 g. Scenario 1 involved human-powered hydroponic system production with an average lettuce weight of 500 g. Scenario 2 represented lettuce production in soil-based agriculture based on data from Ecoinvent 3.8 (lettuce361 production GLO), while Scenario 3 considered lettuce production in a greenhouse based on data from Ecoinvent 3.8 (lettuce360 production, in heated greenhouse GLO).

2.1.5 Life Cycle Impact Assessment (LCIA)

The assessment was performed using SimaPro software version 9.4. The ReciPe 2016 Midpoint (Hierarchist) version 1.07 LCIA method was selected to evaluate 18 environmental impact categories: global warming potential (GWP); stratospheric ozone depletion potential (ODP); ionising radiation potential (IRP); ozone formation potential, human health (OFPh); fine particulate matter formation potential (PMP); ozone formation potential, terrestrial ecosystems (OFPt); terrestrial acidification potential (TAP); freshwater eutrophication potential (FEP); marine eutrophication potential (MEP); terrestrial ecotoxicity potential (TEP); freshwater ecotoxicity potential (FETP); marine ecotoxicity potential (MECP); human carcinogenic toxicity potential (HTPc); human non-carcinogenic toxicity potential (HTPnc); agricultural land occupation potential (ALOP); mineral depletion potential (MDP); fossil depletion potential (FDP); and water deprivation potential (WDP). The ReCiPe 2016(H) V1.07 LCIA method was selected because it is considered the most comprehensive and up-to-date LCIA method. The 18 midpoint level available categories of the method were considered, as they allow the holistic identification of potential trade-offs, cause-effect pathways, and environmental mechanisms during the impact assessment and interpretation steps.

2.2. Life Cycle Costing (LCC)

2.2.1 Goal and Scope

The goal and scope of the LCC adopted the same system boundaries and functional units as those of the LCA, as described in Section 2.1.1. The consumer obtains the lettuces via the human-powered hydroponic system located in a house in the UK (Manchester). The timeframe considered was 2023, and the economic unit used was the British pound sterling. This is the baseline scenario.

2.2.2 Life Cycle Inventory (LCI)

The LCI considered in the LCC was the same as that used in the LCA, as described in Section 2.1.2. in Tables 1 and 2. Table 3 lists the LCI and the cost of each component.

Table 3. Human-powered hydroponic system prototype cost

Component	**Quantity**	**Cost**	
		Each [£]	**Total [£]**
Small white planting pot	6	£ 0.75	£ 4.48
Hose-pipe connector	1	£ 0.93	£ 0.93
Pump	1	£ 1.26	£ 1.26
Pipe (65A) 60cm	1	£ 0.14	£ 0.14
Pipe (40A) 60cm	1	£ 0.14	£ 0.14
65A pipe cap	2	£ 1.00	£ 1.99
40A pipe cap	2	£ 0.14	£ 0.27
Hose connector (PC 10)	4	£ 0.93	£ 3.73
Hose (455 mm, radius 10mm)	1	£ 0.62	£ 0.62
Hose (425mm, radius 8mm)	1	£ 0.62	£ 0.62
12V Battery	1	£ 398.82	£ 398.82
Wood plate	5	£ 0.62	£ 3.11
Sponges (112cell)	1	£ 2.18	£ 2.18
Mini sponges (110 cells)	1	£ 1.43	£ 1.43
Pedal generator	1	£ 112.33	£ 112.33
LED (50cm - Type A)	3	£12.14	£36.41
LED Cable connector (30cm)	1	£12.14	£12.14
LED Power adaptor	1	£12.14	£12.14
Bucket	1	£ 5.00	£ 5.00
Perilla seeds	1	£ 1.29	£ 1.29
Screws	14	£ 0.30	£ 4.20
		Total	£ 603.23

2.2.3 Economic impact assessment methods

The approach followed for the economic assessment consisted of modelling the value of all monetary expenditures for the system boundaries considered (Section 2.1.1), which included the following cost categories: costs to acquire (acquisition cost), operate (operating cost), and maintain (maintenance, repair, and replacement costs) the human-powered hydroponic system.

2.2.3.1 Acquisition cost

The acquisition cost includes inventory, initial procurement, and installation costs.

The inventory cost for all components used in the human-powered hydroponic system was £603.23, as listed in Table 3. Of the total, £398.82, approximately 66% of the total cost, was allocated to the battery alone. No cost was considered for the assembly of the human-powered hydroponic system because it was a prototype, and the authors do not yet know the cost of assembling it once the design has been prepared for mass manufacturing. For this assessment, it was assumed that the prototype human-powered hydroponic system was manually assembled by the end user.

2.2.3.2 Operating cost

In terms of operating costs, the energy required to power the system and the water and fertiliser used were considered. The human-powered hydroponic system requires 30 Wh to operate, which is obtained from the battery, which is charged via human power (e.g. pedalling the generator); therefore, no cost is incurred to power the system. The initial volume of water used to fill the container was 10 l. An amount of 1.4 l every 40 days was necessary to run the system to refill the evaporated and absorbed water. This equals 1.05 l of water used per month. Considering a rate of £3.08 per m^3 (UK North-West Utilities, 2022), the cost of the required water is

$$(10\ l / 1000)\ m^3 * £3.08/m^3 = £0.03.$$

The container was assumed to be emptied and refilled once a year for cleaning purposes.

A recurring cost to refill is calculated:

$$(1.05\ l / 1000)\ m^3 * £3.08/m^3 * 12\ months = £0.04\ per\ year.$$

Fertiliser was periodically used in the system. A 1-litre bottle costs £7.86, and 24 ml is required every 7–10 days (8.5 days were used in the calculation).

$$1000\ ml / 24\ ml = 41.6\ uses\ per\ bottle,$$

with a total duration for the bottle of:

$$41.6 * 8.5\ days = 354\ days.$$

The authors assumed the use of one bottle per year, resulting in a recurring cost of £7.86 per year.

The total operating cost (per year), accounting for water and fertiliser, is

$$£0.03 + £0.04 + £7.86 = £7.93\ per\ year.$$

2.2.3.3 Maintenance, repair, and replacement costs

The costs of maintenance, repair, and part replacement must be added to ensure the accountability of the expenditures incurred to keep the system functional over time.

In terms of component duration, apart from the battery (see Table 3), the authors did not have information about the lifespan of each component of the prototype because the suppliers of the components did not provide these data. Therefore, based on previous studies (Abdollah and Sharareh, 2019), it was assumed that the maintenance and repair costs were approximately 5% of the total inventory cost of the human-powered hydroponic system.

$$5\% * £603.23 = £30.16 \text{ per year}.$$

This cost assumption is used to cover components that eventually require replacement or repair (e.g. generator parts or the small DC motor used in the water pump).

The battery, which is the most likely component of the system to fail first and cause the entire system to stop functioning, has a lifespan of 15 years. Therefore, we considered this to be the lifespan of the human-powered hydroponic system.

3. Results and discussion

The key findings of the LCA and LCC for the human-powered hydroponic system are presented in this section. The environmental impact and economic performance were evaluated and compared with those of conventional soil and greenhouse-based vegetable production methods.

3.1 Life cycle assessment (LCA) results

As shown in Figure 3, the battery was the leading environmental hotspot in 16 of the 18 evaluated impact categories, accounting for 40% (fossil depletion potential) to 85% (terrestrial, freshwater, and marine ecotoxicity potential) of the environmental impacts. The main negative environmental impact of the battery originates from the production stage of Li-ion battery cells, specifically the production of the cathodes and anodes. These components account for 71–98% of the impact of the Li-ion battery cell. The power system was the most significant environmental hotspot in terms of global warming potential (GWP) and ionising radiation potential (IRP), contributing 44% and 53%, respectively. It also ranked second in 14 of the 18 categories (OFPh, PMP, OFPt, TAP, FEP, MEP, TEP, FETP, MEP, HTPnc, ALOP, MDP, FDP, and WDP; Figure 3).

In the case of the power system, the LED strip, power adaptor (i.e. driver), and generator are the primary environmental hotspots (Figure 3). The LED strip was the most significant contributor to the environmental impact of the power system in 13 of the 18 evaluated categories (GWP, ODP, IRP, OFPh, PMP, OFPt, TAP, FEP, MEP, HTPc, ALOP, FDP, and WDP), the power adaptor in 3 (FETP, MECP, and HTPnc), and the generator in 2 (TEP and MDP). In the case of the LED strips, the impact is mainly caused by the electricity consumption required to manufacture the LEDs. In the HTPc category, piping was the second most influential, accounting for 20% of the total environmental impact, and fertiliser was the second most influential environmental hotspot, accounting for 29% of the environmental load for stratospheric ozone depletion.

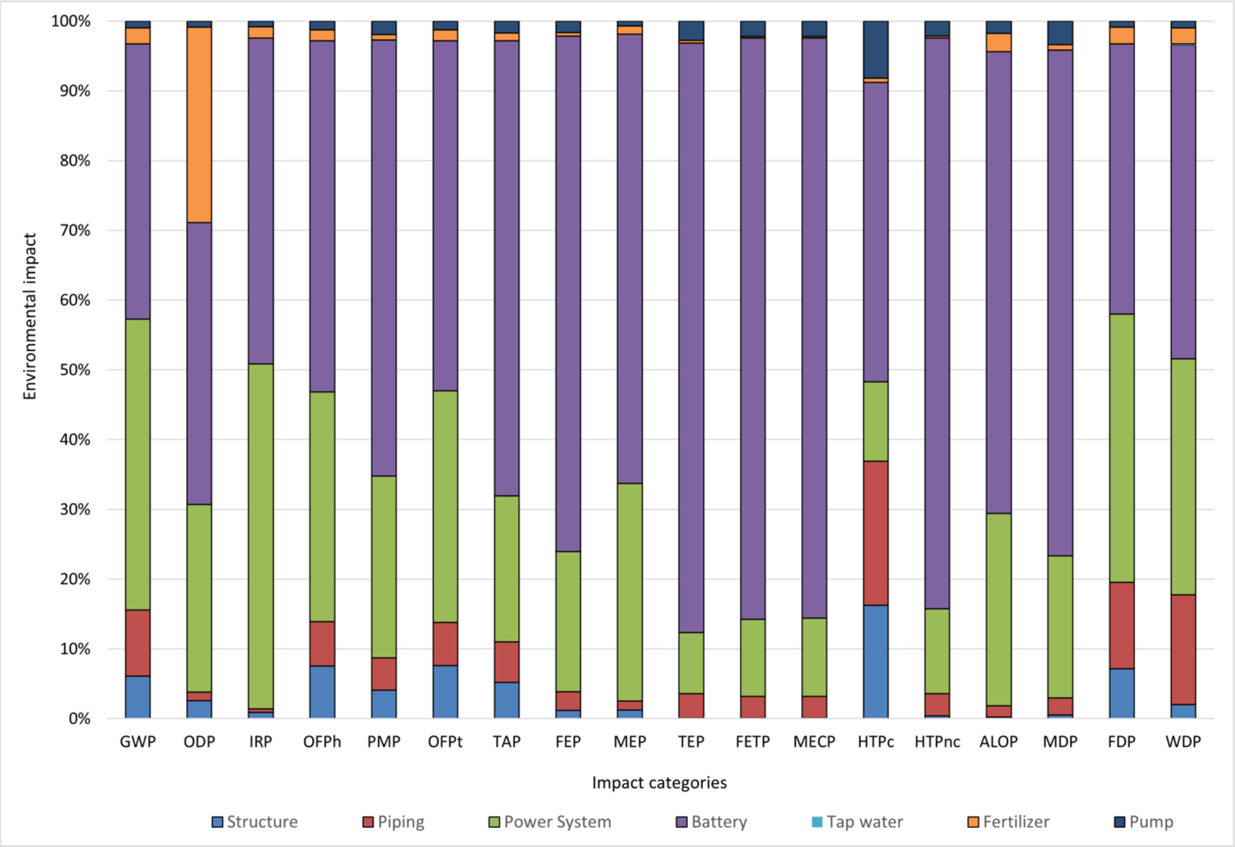


Figure 3. Environmental impact of 1 kg of lettuce produced by the human-powered hydroponic system for the 18 impact categories of ReciPe 2016 Midpoint (Hierarchist) version 1.7. GWP: global warming potential; ODP: stratospheric ozone depletion potential; IRP: ionising radiation potential; OFPh: ozone formation potential, human health; PMP: fine particulate matter formation potential; OFPt: ozone formation potential, terrestrial ecosystems; TAP: terrestrial acidification potential; FEP: freshwater eutrophication potential; MEP: marine eutrophication potential; TEP: terrestrial ecotoxicity potential; FETP: freshwater ecotoxicity potential; MECP: marine ecotoxicity potential; HTPc: human carcinogenic toxicity potential; HTPnc: human non-carcinogenic toxicity potential; ALOP: agricultural land occupation potential; MDP: mineral depletion potential; FDP: fossil depletion potential; WDP: water deprivation potential). The results of each impact category are independent.

In the analysis of the overall environmental impact results, lettuce production in the human-powered hydroponic system demonstrated a lower environmental impact than lettuce production in vertical farming systems, hydroponics, and greenhouses relying on electricity or fossil fuels as an energy source. The impact of the human-powered hydroponic system on global warming was 0.439 kg CO_2 eq./kg per lettuce, a value much lower than those reported for greenhouse lettuce production, which can range from 1.21 CO_2 eq./kg (Blom et al., 2022) to 17.8 kg CO_2 eq./kg (Casey et al., 2022), or hydroponic cultivation produced with electricity from the British grid with 8.9 kg CO_2 eq./kg (Casey et al., 2022), or a commercial vertical farming system in the Netherlands with 8.18 kg CO_2 eq./kg (Blom et al., 2022).

The global warming potential of the lettuce produced in the human-powered hydroponic system falls within the ranges presented for conventional crops, which can vary from 0.16 (Avadí et al., 2021) to 10 kg CO_2 eq./kg lettuce (Casey et al., 2022). Blom et al. (2022) reported a carbon footprint of 0.49 kg CO_2 eq./kg for lettuce produced in open-field farming, whereas Casey et al. (2022) indicated that lettuce supplied from field cultivation imported to Britain from Spain had a carbon footprint of 0.68 kg CO_2 eq./kg. In another study comparing organic and conventional lettuce cultivation systems in Northern Greece, the results showed an environmental impact of 1.28 kg CO_2 eq./kg of lettuce for the organic system and 0.63 kg CO_2 eq./kg of lettuce in a conventional system (Foteinis and Chatzisymeon, 2016). Based on the results of these previous studies, and from the point of view of global warming potential, the human-powered hydroponic system has advantages over greenhouse, hydroponic, and vertical farming production systems, as well as several conventional lettuce production systems.

In other environmental impact categories, such as freshwater eutrophication, the impact of lettuce production using a human-powered hydroponic system (0.434 g P eq.) was higher than that of the conventional lettuce crops, which ranged from 0.026 g P eq. to 0.29 g P eq., and lower than that of vertical farming (3.8 g P eq.) and greenhouse cultivation (33.0 g P eq.; Casey et al., 2022). In conventional agriculture, environmental impacts in relation to this impact category are mostly caused by the excessive use of macronutrients that generate nutrient emissions into the air, water, and soil (Martin-Gorriz et al., 2020), whereas in the human-powered hydroponic system, the impacts on eutrophication are mainly caused by phosphate emissions from leachate directly from tailings impoundment in the operation of copper mines for the production of copper cathodes used in the production of battery anodes. Similarly, sulphur oxides from fossil fuel combustion and ammonia and nitrate emissions from N-fertilisers are the main contributors to the acidification potential in conventional agriculture. In contrast, atmospheric sulphur dioxide emissions from the copper concentrate smelting industry, which is necessary for producing battery anodes, are responsible for the acidification of lettuce produced using the human-powered hydroponic system.

In stratospheric ozone depletion, lettuces grown in the human-powered hydroponic system have an impact of 0.00022 g CFC11 eq., which is comparable to that of lettuces produced using conventional cultivation methods in the United Kingdom, which amounts to 0.00016 g CFC11 eq. However, the impact of the human-powered hydroponic system was lower than that of conventional lettuce production in Spain (0.0013 g CFC11 eq.) and hydroponic cultivation in the UK (0.0055 g CFC11 eq.; Casey et al., 2022). In the case of conventionally grown lettuce, 65% of the impact is related to nitrous oxide ($N2O$) emissions generated during soil biological processes due to nitrogen-based fertilisers. Conversely, in the human-powered hydroponic system, the primary contribution to the impact comes from the batteries, accounting for 40%, followed by nitrogen-based fertilisers at 28%. The impacts of the batteries are also linked to nitrous oxide emissions, which are primarily generated during the production of nitric acid used in the life cycle of copper cathodes.

Owing to the importance of further understanding the effects of the human-powered hydroponic system on the environmental impact categories associated with the consumption of minerals, fossils, water, soil, and toxic substances, a more detailed analysis was conducted through sensitivity analysis and scenario modelling.

3.1.1 Sensitivity analysis

Owing to the high impact of the manufacturing stage on the total environmental impact of the system life cycle, particularly the battery and power systems, the increase in productivity (i.e. producing more grams of lettuce per cycle) was evaluated through a sensitivity analysis. The human-powered hydroponic system produced an average weight of 200 g per lettuce. However, literature indicates that under optimum indoor conditions, lettuce size can reach up to 322 g, whereas under optimum outdoor conditions, it can reach up to 781 g (Ezziddine et al., 2021). We conducted a conservative sensitivity analysis to evaluate the environmental impacts of increasing lettuce size (higher productivity yield of the system) by varying the average weight of lettuce produced by the system from 200 to 500 g. As shown in Figure 4, the environmental impact decreased with increasing lettuce weight, with reductions of approximately 60% in 17 of 18 impact categories when the weight of the lettuce produced reached 500 g. Only the stratospheric ozone depletion impact category showed a less pronounced reduction (43% when the lettuce size was increased to 500 g) because this category is influenced by fertiliser use, which increases with higher yields.

Therefore, improving the productivity of the system to increase its yield is a valuable strategy for reducing the environmental impact of the human-powered hydroponic system. Thus, the production of 500 g of lettuce using the human-powered hydroponic system could result in a global warming impact of 0.18 kg CO_2 eq./kg per lettuce, a value very close to the 0.15 kg CO_2 eq./kg of lettuce generated by conventional agriculture systems (Casey et al., 2022).

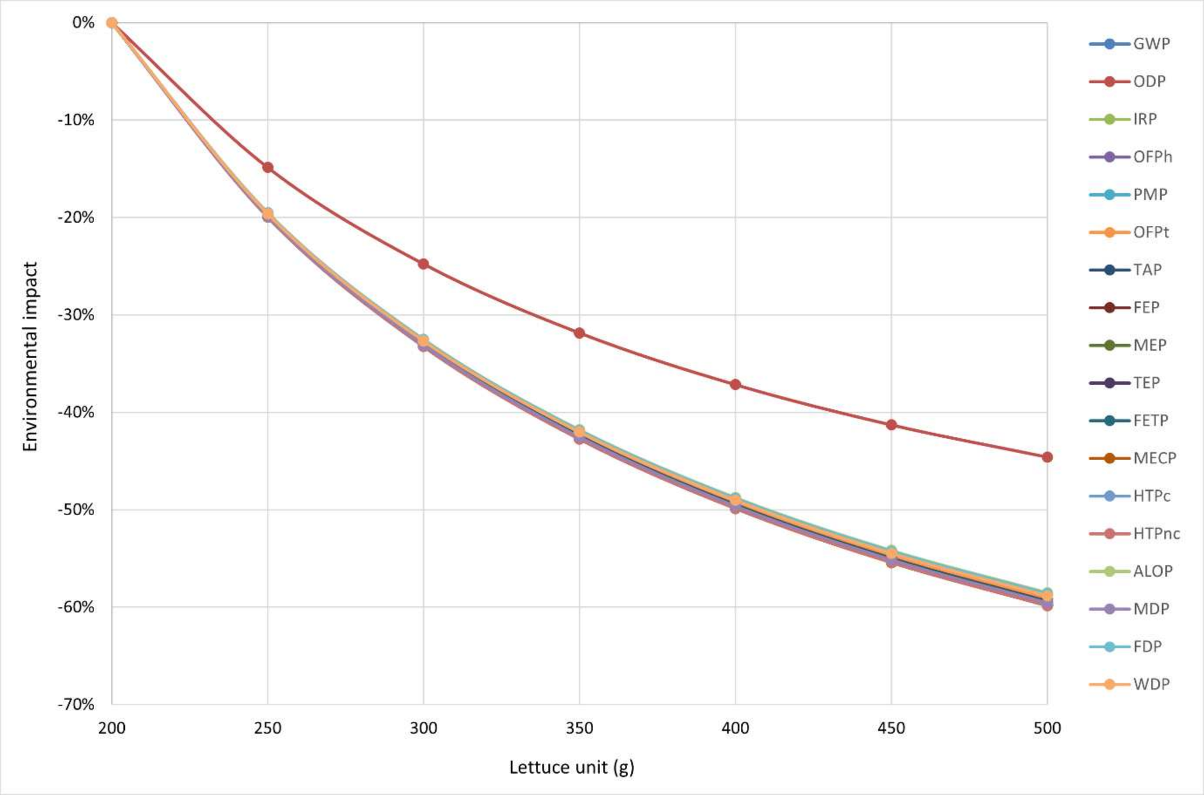


Figure 4. Sensitivity analysis of lettuce yield increase in the human-powered hydroponic system.

3.1.2 Scenario analysis

Based on the modelling of baseline lettuce production (200 g) using the human-powered hydroponic system (**Scenario 0**) and the sensitivity analysis with lettuce of an average weight of 500 g (**Scenario 1**), a comparative scenario analysis was conducted by adding two additional scenarios: conventional soil-based produce (**Scenario 2**) and greenhouse-based (**Scenario 3**) lettuce production, with data obtained from the Ecoinvent database. Figure 5 presents the results of the scenario comparison. Lettuce produced by the human-powered hydroponic system had a lower environmental impact than lettuce produced in greenhouses in 14 of the 18 impact categories evaluated (GWP, ODP, IRP, OFPh, PMP, OFPt, TEP, FEP, MEP, HTPc, HTPnc, ALOP, FDP, and WDP). In the remaining four categories (terrestrial ecotoxicity potential, freshwater ecotoxicity potential, marine ecotoxicity potential, and mineral depletion potential), lettuce produced in the human-powered hydroponic system had a higher impact than lettuce produced in conventional soil-based or greenhouse agriculture.

Terrestrial ecotoxicity (TEP), freshwater ecotoxicity (FETP), and marine ecotoxicity potential (MECP) are the impact categories for ecotoxicity. The effects in these impact categories were caused by copper mining and emissions to the air (TEP), water (FETP), and water with chromium VI (MECP). Among these impact categories, the environmental impact associated with battery manufacturing accounted for approximately 85%. In the mineral resource scarcity category, the consumption of metals such as copper, molybdenum, and iron, which are mainly sourced for battery production, represents the most significant environmental burden.

When comparing the human-powered hydroponic system with conventional lettuce production, 500 g of lettuce grown in the human-powered hydroponic system (Scenario 1) generated higher impacts than conventional soil-based lettuce production (Scenario 2) in 11 of the 18 evaluated impact categories (GWP, IRP, PMP, TAP, FEP, TEP, FETP, MEP, HTPc, HTPnc, and MDP; Figure 5). In the fossil fuel resource scarcity category, they generated an equivalent impact (0.048 kg-oil eq.). Conventional soil-based production methods, contrariwise, had the greatest impact on the remaining six categories (ODP, OFPh, OFPt, MEP, ALOP, and WDP).

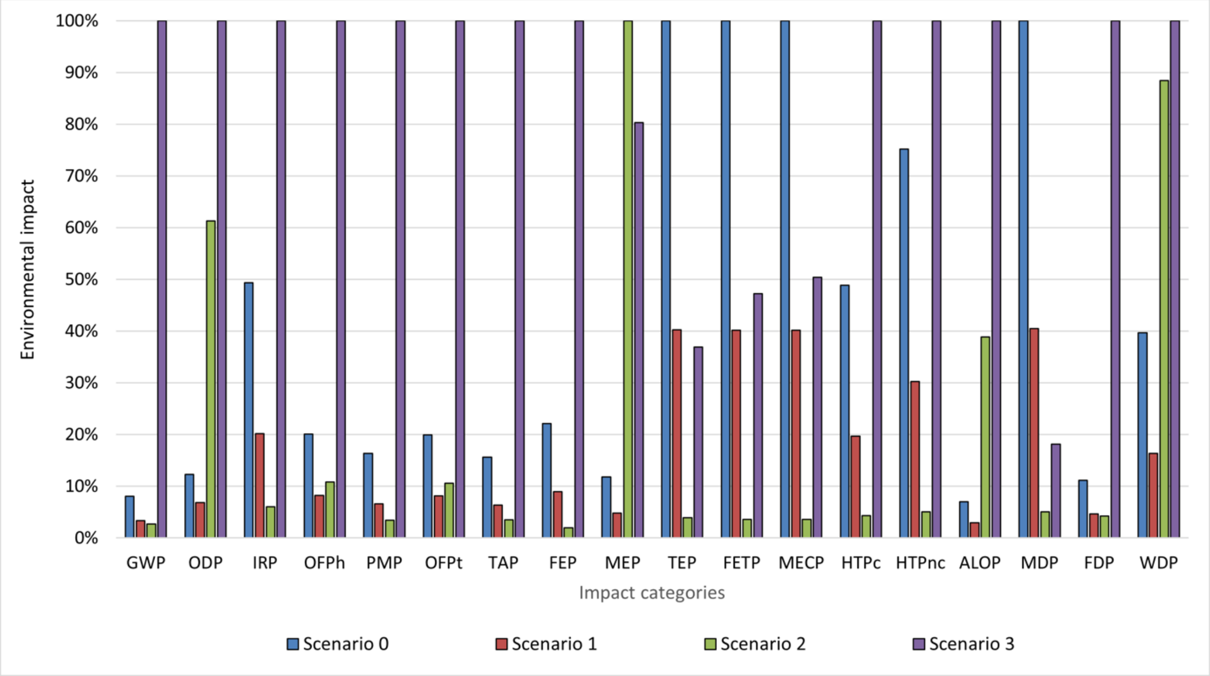


Figure 5. Comparative scenario analysis of 1 kg of lettuce (FU) across different agriculture production systems. Scenario 0: 200 g of lettuce grown in the human-powered hydroponic system; Scenario 1: 500 g of lettuce grown in the human-powered hydroponic system; Scenario 2: lettuce grown in soil-based agriculture; Scenario 3: lettuce grown in greenhouses. For a full definition of impact category acronyms, see the caption of Figure 3.

3.2 Life cycle costing (LCC) results

3.2.1 Total cost

The total cost incurred in the first year was £641.32. The cost breakdown is shown in Figure 6.

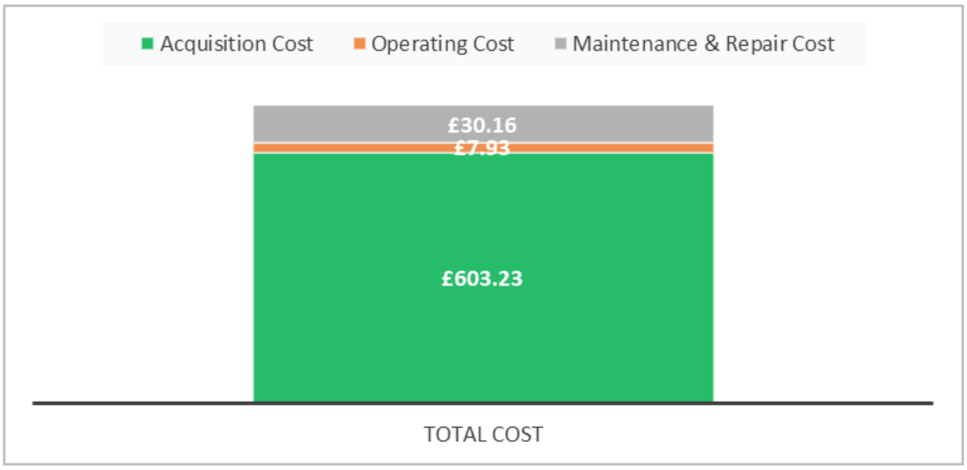


Figure 6. Total cost breakdown of the human-powered hydroponic system.

The acquisition cost accounted for 94% of the total cost. While the acquisition cost is only upfront, other costs – operating, maintenance, and repair – are recurring. The graph in Figure 7 shows the evolution of the total, acquisition, operating, and maintenance repair costs over a 15-year lifespan (the lifespan of the human-powered hydroponic system). An inflation rate of 2% per year was considered for the recurring costs.

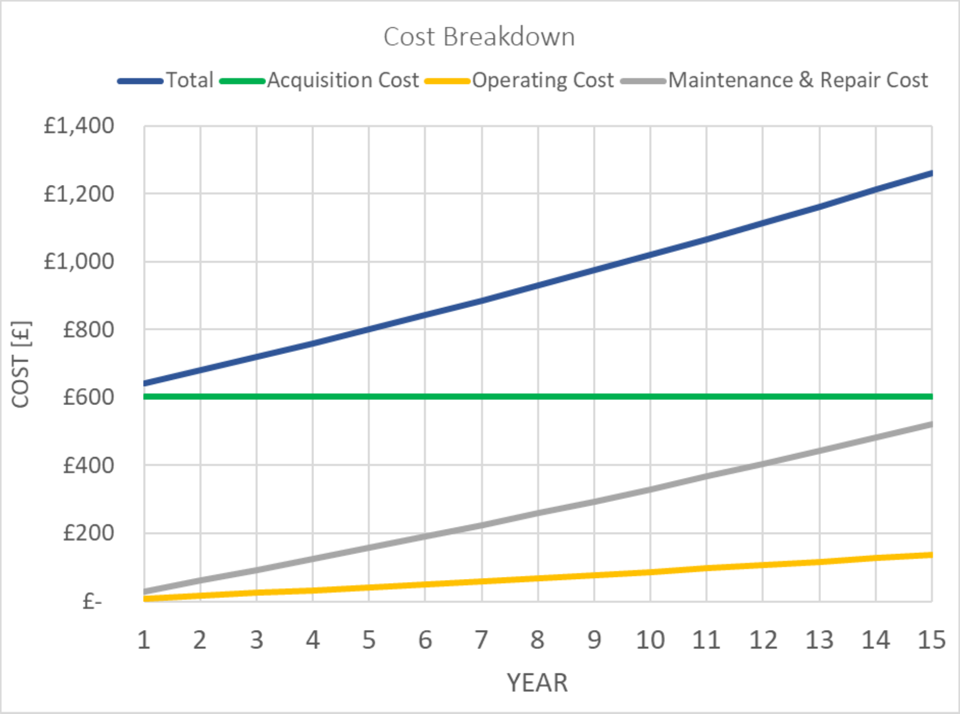


Figure 7. Annual total and cost breakdown of the human-powered hydroponic system over its 15-year lifespan.

The total cost of the human-powered system operating for 15 years was £1,261.98.

3.2.2 Sensitivity analysis

The human-powered hydroponic system had a 40-day cycle from seedling to harvest. Considering the production of a 200 g weight average per lettuce, a total of 1.20 kg of lettuce is produced in such a cycle, equal to 10.95 kg in a year and 164.25 kg in 15 years, with a total cost of £1261.98.

Similarly, considering the increased average weight of 500 g per lettuce, a total of 3.0 kg of lettuce was produced in such a cycle, which equals 27.38 kg in 1 year and 410.70 kg in 15 years. Considering the proportional increase in fertiliser and water usage, the total cost was projected to be £1467.72.

The cost per kilogram compared to the production volume during the 15-year lifespan of the human-powered hydroponic system is shown in Figure 8. These values were calculated by dividing the total cost by the production weight.

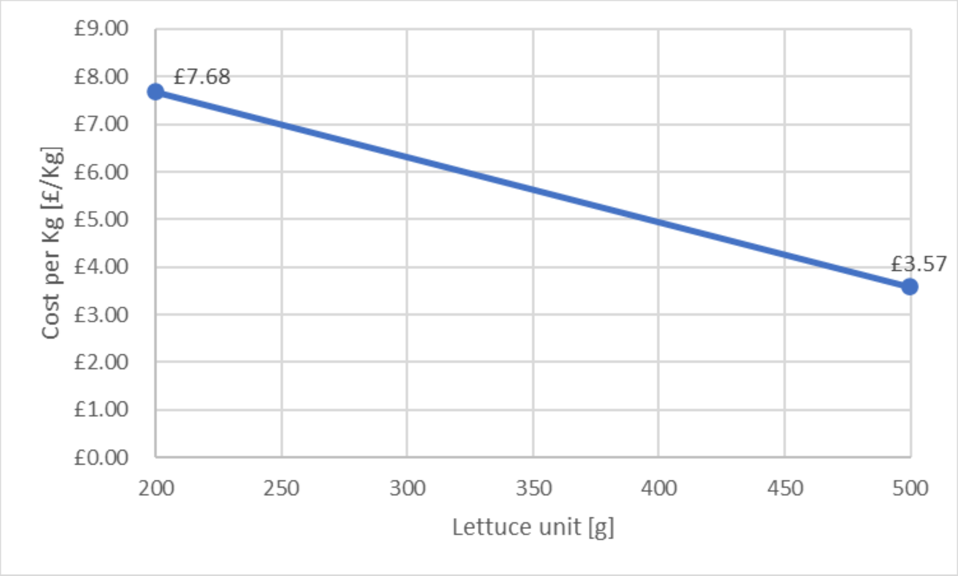


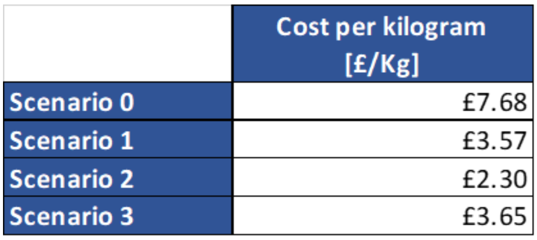
Figure 8. Sensitivity analysis (cost) of the lettuce yield increase in the human-powered hydroponic system.

3.2.3 Scenario analysis

The four scenarios described in Section 2.1.4 are assessed and compared in terms of economic costs. Table 4 presents the cost per kilogram of lettuce produced under the four LCA scenarios described in Section 3.1.2. For Scenarios 0 and 1, the resulting cost refers to that of Scenarios 0 and 1, respectively, while for Scenarios 2 and 3, the national average wholesale prices of UK-grown horticultural produce (GOV UK wholesale fruit and vegetable prices weekly average, 2023) were used.

Table 4. Scenario cost per kilogram

Scenario	Cost per kilogram [£/Kg]
Scenario 0	£7.68
Scenario 1	£3.57
Scenario 2	£2.30
Scenario 3	£3.65



	Cost per kilogram [£/Kg]
Scenario 0	£7.68
Scenario 1	£3.57
Scenario 2	£2.30
Scenario 3	£3.65

The cost of producing lettuce in Scenarios 0–3 (Table 4) is shown (Figures 9–10) over 15 years (the lifespan of the system) to determine the annual cost of producing lettuce in these four scenarios. An inflation rate of 2% per year was included in the recurring costs for Scenarios 0 and 1 and in the total costs for Scenarios 2 and 3.

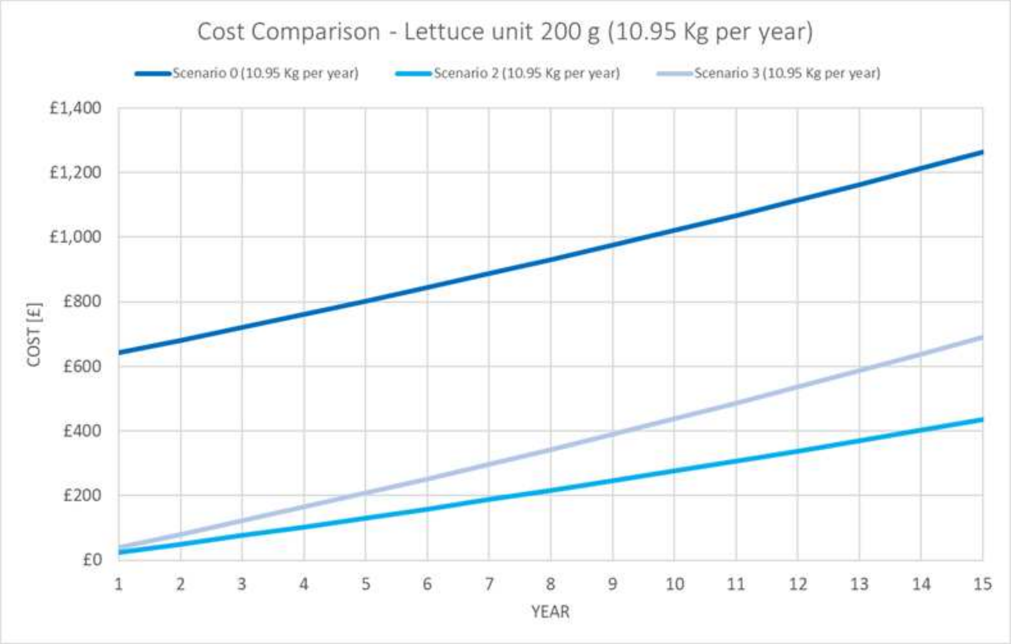


Figure 9. Scenario comparison with lettuce unit 200 g (15-year lifespan)

Figure 10. Scenario comparison with lettuce unit 500 g (15-year lifespan)

Figure 9 shows a comparison of costs between the production of a 200 g lettuce unit using the human-powered hydroponic system (Scenario 0), conventional soil-based open-field agriculture (Scenario 2), and greenhouses (Scenario 3). The findings indicate that Scenario 0 is costlier for the consumer than Scenarios 2 and 3 are. Additionally, it is evident that the break-even point between Scenarios 0, 2, and 3 could not be reached within the 15-year lifespan of the system. Scenario 1 was not reported because it involved the production of a lettuce unit weighing 500 g.

Figure 10 shows the scenario considering the production of a 500 g lettuce unit with the human-powered hydroponic system (Scenario 1), which achieves a break-even point with Scenario 3 between years 10 and 11, whereas the break-even point is not achievable within the considered lifespan with Scenario 2, although it could be reached if the human-powered hydroponic system had a longer lifespan. Scenario 0 was not reported because it involved the production of a lettuce unit weighing 200 g.

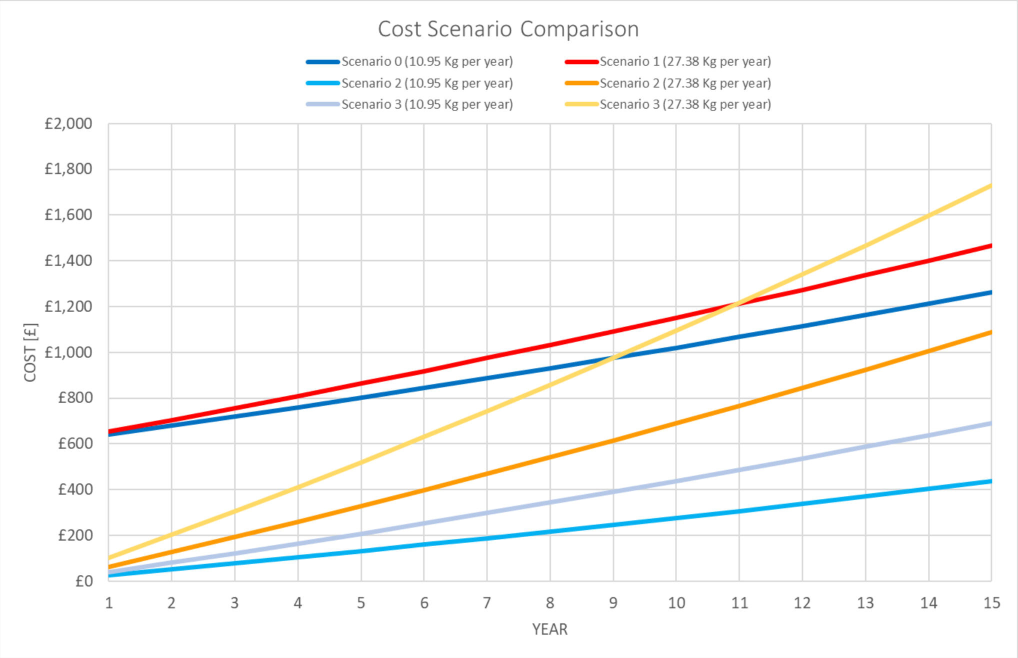


Figure 11. Overall cost scenario comparison

Figure 11 presents an overall comparison of all scenarios. It is important to note that only Scenarios 0 (10.95 Kg per year), 2 (10.95 Kg per year), and 3 (10.95 Kg per year) or Scenarios 1 (27.38 Kg per year), 2 (27.38 Kg per year), and 3 (27.38 Kg per year) can occur simultaneously when making a comparison based on the same amount of lettuce.

3.3 Discussion

This study analyzes the environmental impact and cost of a human-powered hydroponic system by modelling the environmental impact and cost of the system life cycle based on likely scenarios to understand its impact and identify opportunities to improve its environmental and economic performance. After performing a comparative assessment between the human-powered hydroponic system and conventional soil-based and greenhouse agriculture methods, as well as reviewing the existing literature on the environmental impact assessment of other agricultural methods (e.g. conventional open-field agriculture, grid-powered hydroponics, and greenhouses), it is clear that the human-powered hydroponic system has a smaller environmental impact in terms of global warming potential (GWP) than most other existing agricultural methods. For example, the impact on global warming of the human-powered hydroponic system is 0.439 kg CO_2 eq./kg per lettuce, a value much lower than those reported for greenhouse lettuce production, which can range from 1.21 CO_2 eq./kg (Blom et al., 2022) to 17.8 kg CO_2 eq./kg (Casey et al., 2022), and hydroponic cultivation using electricity from the British grid with 8.9 kg CO_2 eq./kg (Casey et al., 2022), or a commercial vertical farming system in the Netherlands with 8.18 kg CO_2 eq./kg (Blom et al., 2022).

The human-powered hydroponic system's lettuce production (0.434 g P eq.) has a higher environmental impact than conventional lettuce crops (0.026–0.29 g P eq.) and is lower than vertical farming (3.8 g P eq.) and greenhouse cultivation (33.0 g P eq.) in the freshwater eutrophication impact category (Casey et al., 2022). The excessive use of macronutrients in conventional agriculture contributes to nutrient emissions into the air, water, and soil (Martin-Gorriz et al., 2020), whereas phosphate emissions are created from leachate directly from tailing impoundments in copper mines for the production of copper cathodes used in the production of battery anodes in the human-powered hydroponic system. The acidification potential in conventional agriculture is mostly attributed to the release of sulphur oxides resulting from the combustion of fossil fuels as well as the emissions of ammonia and nitrates from the use of nitrogen-based fertilisers. However, it should be noted that the smelting industry of copper concentrate, an essential component in the production of battery anodes, emits atmospheric sulphur dioxide. This emission has been identified as a contributing factor to the acidity of lettuce cultivated using the human-powered hydroponic system.

In the stratospheric ozone depletion impact category, lettuces grown in the human-powered hydroponic system have an impact of 0.00022 g CFC11 eq., which is comparable to that of lettuces produced using conventional cultivation methods in the United Kingdom, which amounts to 0.00016 g CFC11 eq. However, the impact of lettuce produced with the human-powered hydroponic system was lower than that associated with conventional lettuce production in Spain (0.0013 g CFC11 eq.) and hydroponic cultivation in the UK (0.0055 g CFC11 eq.; Casey et al., 2022).

In addition, the sensitivity analysis showed that enhancing the productivity (yield) of the human-powered hydroponic system generates substantial reductions in environmental impact, with a potential decrease of approximately 60% in most environmental impact categories. This finding highlights the importance of improving the productivity of the human-powered hydroponic system. Thus, the production of 500 g of lettuce using the human-powered hydroponic system could result in a global warming impact of 0.18 kg CO_2 eq./kg per lettuce, a value very close to the 0.15 kg CO_2 eq./kg for lettuce generated by conventional soil-based agricultural systems (Casey et al., 2022).

When evaluating the total life cycle costs of the human-powered hydroponic system, the cost of producing 200 g of lettuce was higher (£7.86/kg) for consumers than for purchasing lettuce cultivated through conventional soil-based open-field agriculture and greenhouses (£2.30/kg and £3.65/kg, respectively). It is thus not feasible to reach a break-even point within a 15-year lifespan. The human-powered hydroponic system could achieve the break-even point with greenhouse-produced lettuce after approximately 10 to 11 years if the human-powered hydroponic system increased its productivity (yield) and produced lettuces of 500 g instead of 200 g. However, when compared with conventional soil-based open-field agriculture, the human-powered hydroponic system did not reach the break-even point within the considered lifespan, even when the system was assumed to increase its productivity and produce 500 g of lettuces. However, it is worth noting that if the human-powered hydroponic system had a longer lifespan, the break-even point could potentially be reached. The attainment of the break-even point for the human-powered hydroponic system, in comparison to the cost of lettuce produced with other agricultural methods, could be achieved through changes in some variables, including adjustments to inflation rates, an extension of the battery lifespan (and consequently, the system lifespan), or an increase in the quantity of lettuce produced by the human-powered hydroponic system (i.e. a greater yield in kilograms per unit).

4. Conclusions

This study assessed the environmental and economic implications of a novel human-powered hydroponic system using life cycle assessment (LCA) and life cycle cost analysis (LCC) methods. This study assessed various scenarios to identify opportunities for improving both the environmental and economic performance of the human-powered hydroponic system.

The life cycle assessment showed that the battery stands out as the primary environmental hotspot, contributing significantly (40-85%) in 16 of the 18 impact categories. The power system is another key contributor to global warming and ionising radiation, accounting for 44% and 53%, respectively. Both the battery and power system play critical roles in the system’s operation,. These results suggest that any improvements in the design and manufacturing of the battery or power system (i.e. generator, LED cable connector, LED, and LED power adaptor) could significantly reduce the overall environmental impact of the human-powered hydroponic system.

Another crucial issue is the sensitivity of the production unit. Based on our findings, it is evident that the break-even point is unlikely to be reached within a 15-year lifespan with an average production of 200 g per lettuce. However, for a higher yield of 500 g per lettuce, the human-powered hydroponic system becomes economically viable sooner, specifically between the 10th and 11th years. Hence, reducing the acquisition costs and increasing the productivity of the system (yield) could further minimise the environmental impact and facilitate reaching the cost break-even point.

Future studies of human-powered hydroponic systems should explore additional scenarios that were not assessed in this study, as these might capture other potential scenarios which could yield different assessment results. For instance, they could investigate the impact of food loss and waste, analyse other food product categories, and consider the production of out-of-season, high-value, and low-supply food products. Furthermore, there is potential for surplus energy generation and utilisation in other household services that would require system allocation and environmental load distribution. Conversely, there may be an energy deficit that necessitates the use of household electricity or integration of renewable energy sources. The developed human-powered hydroponic system could also be redesigned to further reduce its environmental impact and cost by implementing several sustainable design strategies to address the key engineering design requirements associated with the main environmental impacts and costs identified in this study: 1) reducing the energy requirements of the system during the use phase; 2) increasing its yield; 3) reducing the environmental impact of its manufacturing stage; and 4) increasing its lifespan, which could be achieved by increasing the durability of the components within the system to avoid failure and thus extend their lifespan. Batteries are one of these key components.

Declaration of competing interests

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

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Supplementary material

Human-powered hydroponic system

a) Prototype

The human-powered hydroponic system developed in this study was designed to be fully powered by human power to grow lettuce for domestic indoor applications, although other similar crops can also be grown. The hydroponic technique used by the system is ‘deep flow’, which is one type of the continuous open circulating flow solution culture methods (Khan et al., 2018). As the system does not incorporate any smart climate control monitoring devices, the carbon dioxide concentration, nutrient solution (e.g. composition, pH, electrical conductivity), air temperature, light intensity, and air humidity are controlled manually by the user.

b) Performance of the prototype

The human-powered hydroponic system (Figure 1) is a 1:1 scale working functional early prototype, so the performance data obtained are based on preliminary early trial testing, not exhaustive testing of a final detailed system ready for mass production.

Since the human-powered hydroponic system has been designed for indoor domestic applications (not greenhouses) and it is not equipped with any ‘smart’ systems to automatically control the environmental parameters (e.g. light, temperature, humidity, CO_2 levels) where the human-powered hydroponic system is used, these parameters must be controlled manually by the user via the heating/cooling and air exchange facilities of the room of the house where it is located. This implies a reduction in total energy consumption because of the warmer conditions in the domestic settings. However, this also means that the control of environmental parameters is less precise and fine-tuned for the environmental needs of the specific crop grown in the human-powered hydroponic system, and the quantity and quality of the yield might not be optimal. Similarly, the solution properties (e.g. pH, EC, nutrients contained, and fertilisers) are also controlled manually by the user; therefore, some basic knowledge of hydroponics and specific instruments is required to measure the pH, EC, and nutrients (e.g. fertilisers) of the solution.

Performance of components/system	**Quantity**	**Unit**
Lighting (90 LEDs units x 0.05 W each LED) – 20 h/day	0.09	kWh/day
Water pump (3 W x 24 h/day)	0.072	kWh/day
Batteries (12 v, 30Ah lithium battery) 3000 charges with 100% efficiency – storage capacity	0.384	kWh
Water tank	10	litres
Amount of vegetables produced per 40 days cycle	6 x 200: 1200	gr

Vegetables produced	6	Lettuce
Lifespan of the system	15	Years
Fertilisers required:		gr/cycle
NPK	2.40	
Calcium ammonium nitrate	1.45	
Inorganic potassium and K_2O	2.02	
Urea	0.09	
Human-powered generator	up to 100	Wh
Total weight of the system (with empty water container)	12.2	kg

Table 1. Performance of the human-powered hyrdroponic systems

c) *How the prototype works*

The prototype requires energy to power the LED lighting system and water pump. This energy is obtained via the human-powered generator, which also helps the user exercise and stay active simultaneously. When the user is pedalling, the generator produces energy stored in the battery that powers the hydroponic system (LED lighting and water pump). The total energy consumption of the human-powered hydroponic system is 0.162 kWh/d, which is equivalent to the energy generated from pedalling the 'generator' for 1.5 h. The battery has the capacity to store enough energy that the hydroponic system can be used for two days when the user is not performing exercises (pedalling) every day. The prototype also requires water which is stored in a water container and pumped using a water pump, and fertiliser must be added to the water (solution) for the vegetables to grow. The pH and electrical conductivity (EC) of the solution must be periodically measured and manually controlled to ensure optimal values for lettuce growth. This requires a basic knowledge of hydroponics and tools for measuring the pH and EC of the solution. In addition, the light, temperature, humidity, and CO_2 levels where the human-powered hydroponic system is located are also critical for the growth of lettuce, and these have to be manually controlled by the user by controlling the domestic heating and cooling systems and the air exchange in the room where the hydroponic system is located. A more advanced version of this human-powered hydroponic system could also use 'smart' systems to automatically control the environmental parameters and nutrients in the solution, but this would increase the cost and the energy required to power the system. Commercial hydroponic systems located in greenhouses or advanced vertical systems are more automated, which may lead to higher yields. However, they are more expensive and consume more energy.

Ecoinvent processes selected for the life cycle assessment (LCA):

Part of the system	**Material**	**Ecoinvent 3.8**
Small white planting pot	PP	Polypropylene, granulate {GLO}| market for | Cut-off, S
Hose-pipe connector	ABS	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, S
Pipe (60 cm)	PVC	PVC pipe E
Hose (large)	PUR	Polyurethane, flexible foam {RoW}| market for polyurethane, flexible foam | Cut-off, S
Pipe cap (black)	PVC	PVC pipe E
Hose connector	PVC	PVC pipe E
	Brass	Brass {RoW}| market for brass | Cut-off, S
Pump	Aluminium	Aluminium, wrought alloy {GLO}| market for | Cut-off, U
	Cast iron	Cast iron {GLO}| market for | Cut-off, U
	Copper	Copper, cathode {GLO}| market for | Cut-off, U
	PVC	Polyvinyl Chloride, suspension polymerised {GLO}| market for | Cut-off, U
	Chromium steel	Steel, chromium steel 18/8, hot rolled {GLO}| market for | Cut-off, U
	Rubber	Synthetic rubber {GLO}| market for | Cut-off, U
Generator	Screw (steel)	Steel wire rod/GLO¿
	Hollow screw (ABS)	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, S
	Hollow screw (brass)	Brass {RoW}| market for brass | Cut-off, S
	Bar (steel)	Steel rebar/GLO
	Gears (steel)	Steel hot rolled coil/GLO
	Other parts (steel)	Steel hot rolled coil/GLO

	Pedal (ABS)	Acrylonitrile-butadiene-styrene copolymer {GLO}| market for | Cut-off, S
	Rubber parts	Synthetic rubber {GLO}| market for | Cut-off, S
LED Light	LED	Light emitting diode {GLO}| market for | Cut-off, S
LED cable connector		Cable, unspecified {GLO}| market for | Cut-off, S
LED power adaptor		Power adapter, for smartphone {GLO}| market for power adapter, for smartphone | Cut-off, S
Battery Lithium 12V 30Ah	Battery materials	Battery, Li-ion, rechargeable, prismatic {GLO}| production | Cut-off, S
Wood plate	MDF	Medium-density fiberboard (MDF), at MDF mill/m3/RNA
Sponge (large)	PU	Polyurethane, flexible foam, flame retardant {GLO}| market for polyurethane, flexible foam, flame retardant | Cut-off, S
Bucket	PP	Injection moulding, rigid polypropylene part, at plant/kg/RNA
Screws	Aluminium	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | Cut-off, S

Table 1

Summary of studies reportingenvironmental impact assessments of hydroponic systems

Reference	Types of agriculture system assessed	Power source	Application used	Methods for EI assessment	Types of agriculture	Key findings
Pinho et al. (2022)	FLOCcponic (Integration of biofloc with hydroponic)	Grid power	Commercial targeted	Emergy synthesis	Lettuce	FLOCponic is considered sustainable for food production and more efficient than stand-alone hydroponic; however, improvements should be made to reduce electricity consumption
Ghasemi-Mobtaker et al. (2022)	Hydroponic for fodder	Grid power and natural gas	Commercial targeted	Life cycle assessment (LCA)	Fodder	Consumption of non-renewable energy increases the environment impact significantly
Blom et al. (2022)	Hydroponic greenhouse & vertical farming (VF)	Grid power	Commercial targeted	Life cycle assessment (LCA) - focusing on carbon emissions (GWP) impact category	Lettuce	Carbon footprint of vertical farming was 16.7 times greater than open-field farms, 6.8 times greater than soil-based greenhouses, and 5.6 times greater than hydroponic greenhouses, and the highest impact of the VF was allocated in the use phase, mainly from electricity consumption
Romeo et al. (2018)	Vertical farming (VF)	Grid power	Commercial targeted	Attributional cradle-to-gate life cycle assessment (LCA)	Lettuce	Hydroponic vertical farms perform better than cultivation in heated greenhouses and open-field farms. Consumption of grid power is a determinant factor, but renewable energy input can significantly lower environmental impact
Urbano et al. (2022)	Hydroponic	Grid power	Commercial targeted	Life cycle assessment (LCA)	Tomato	Transport means is a determining factor when comparing eight scenarios of fresh tomato supply to urban citizens
Rothwell et al. (2016)	Hydroponic (Outdoor)	Grid power (coal)	Commercial targeted	Life cycle assessment (LCA) - focusing on global warming potential impact category	Lettuce	Electricity accounted for approximately 50% of the GWP indicator impact category, and fertilisers, diesel, and transplants were other areas of high impact for this environmental impact category
Chen et al. (2020)	Aquaponic vs Hydroponic	Grid power vs renewable scenario	Commercial targeted	Life cycle assessment (LCA)	Lettuce	The EIs of the HS were twice as high as the impacts generated by the aquaponic system. Energy consumption caused the highest environmental impact in both the systems. The results showed that if the source of the electricity used to power lighting and greenhouse heating was changed from coal to natural gas, the EP (eutrophication potential) of hydroponics would be lower than that of aquaponics. If the primary energy source was replaced by renewable energy (wind power), the HS would become more sustainable than the aquaponic system
Casey et al. (2022)	6 Hydroponics	Grid power	Commercial targeted	Life cycle assessment (LCA)	Lettuce	Large environmental footprints occur when powering the hydroponic system. If renewable energy is used to power the systems, HSs could produce smaller carbon footprint than most field-based agriculture methods
Ntinas et al (2020)	Hydroponic	Grid power and renewable (Solar) scenario	Commercial targeted	Life cycle assessment (LCA)	Tomato	Tomato production in high-tech greenhouses using solar power can be more sustainable than conventional greenhouses; thus, energy, water, fertiliser, and associated CO_2 emissions can be saved
Udovichenko et al. (2021)	Hydroponic	Hybrid renewable energy system (solar and heat pump)	Commercial targeted	Life cycle assessment (LCA) - focusing on greenhouse gas (GWP) impact category	Lettuce	Greenhouse gas (GHG) emissions generated from local hydroponic lettuce production, aided by a hybrid renewable energy system (HRES), are three times greater than those emitted by transporting an equivalent quantity of food from southern California, USA. The life cycle cost showed that the cost to produce lettuce from the case study facility is comparable to the price of lettuce available from traditional import, which shows a promising potential.

Table 2

Summary of studies reporting economic assessments of hydroponic systems

Reference	Types of Hydroponic	Application	Assessment Target	Economic Assessment Methods	Key findings
Udovichenko et al. (2021)	Hydroponic	Commercial targeted	Hybrid renewable energy system (solar and heat pump)	Life cycle cost analysis (operating cost)	The life cycle cost showed that the cost to produce lettuce from the case study facility is comparable to the price of lettuce available from traditional import, which shows promise. The unit cost of lettuce produced from this facility was therefore 4.47 ± 0.01 $/kg, whereas that of the price of local lettuce in the community was estimated at 5.86 ± 0.29 $/kg. No food-miles cost is a significant opportunity for cost reduction
Gumisiriza et al. (2022)	New hydroponic with no pump	Domestic	Electricity cost from using no pump	Cost benefit analysis (Net present value (NPV), profitability index (PI), internal rate of return (IRR), and non-discounted payback period (NDPBP)	Significant cost benefits could arise from operating a passive hydroponic system (no pump and light emitting diode (LED) over time due to no electricity consumption), although this is only possible in high solar regions like Africa
Nisha et al. (2019)	NFT (Nutrient Film Technique)	Commercial and domestic	Water conservation	Literature review	Successful production of leafy as well as other vegetables with 70–90% water savings throughout the use phase. Additional cost savings can be generated for advanced automated operation to replace labour and reach break-even on the initial manufacturing cost over time