Sustainable Production and Consumption 51 (2024) 105–117

Contents lists available at ScienceDirect

Sustainable Production and Consumption

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

A life cycle assessment of protein production from wheatgrass: Optimization potential of a novel vertical farming system

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ARTICLE INFO

Editor: Dr. Cecile Chéron-Bessou

Keywords:
Life cycle assessment (LCA)
Alternative protein
Wheatgrass
Vertical farming (VF)

ABSTRACT

The global protein demand is expected to keep increasing due to a growing global population, combined with changing social demography and other factors. OrbiPlant®, a novel vertical farming technology developed in Germany, is used to cultivate wheatgrass (*Triticum aestivum*) as one possible solution for realizing a sustainable protein supply to meet this challenge. The objective of this study was to investigate the environmental impacts of wheatgrass protein concentrate powder produced in the novel vertical farming system and compare it with traditional protein sources (cheese and soy protein). To achieve this, a 'cradle-to-gate' life cycle assessment (LCA) was performed using OpenLCA software and Environment Footprint 3.1 method. The results show that wheatgrass protein from vertical farming has lower environmental impacts than cheese protein in terms of terrestrial eutrophication, and land use, similar impacts on freshwater ecotoxicity and particulate matter, but higher impacts in other categories. Due to the high environmental impact of the current Germany electricity mix, the overall environmental performance of wheatgrass protein remains non-competitive to traditional protein sources. By optimizing production, the environmental impact can be reduced to just 57.8 % of the cheese protein. This finding highlights the potential of the investigated wheatgrass protein from vertical farming system to reduce environmental impacts when substituting animal-based protein. Furthermore, it emphasizes the importance of utilizing renewable energy sources.

1. Introduction

Future presents significant challenges in addressing the increasing protein demand, driven by the simultaneous growth in global population and increased consumption of animal-based foods, particularly notable in developing countries (United Nations, 2019; Wang, 2022). Protein is essential for humans due to its critical role in various physiological functions, as it is composed of amino acids, building blocks necessary for the structure, function, and regulation of tissues and organs (Michaelsen and Greer, 2014; Pedersen and Cederholm, 2014). However, the global food supply chain carries a significant responsibility, accounting for approximately 26 % of anthropogenic greenhouse gas (GHG) emissions (Poore and Nemecek, 2018). Particularly, animal-based food production is identified as a major contributor, as highlighted by numerous review studies showcasing the high climate change and water use impact associated with meat production (Clune et al., 2017; Poore and Nemecek, 2018; Clark et al., 2019; Gaillac and Marbach, 2021). Besides, the limited availability of arable land will pose a significant challenge for the future food supply chain as well (Gomiero, 2016). To achieve a balance between environmental sustainability and ensuring an adequate protein supply, there is an increasing need for more sustainable protein supply chains (Henchion et al., 2017).

Within the European Union (EU), the current dietary pattern is characterized by a high ratio of animal-based proteins. Based on FAOSTAT data, animal-based food constituted over 55 % of the total protein supply in the EU-27 in 2019. In Germany, this figure was slightly higher, reaching 59 % (FAO, 2023). The European Green Deal, which was proposed in 2019, outlined the EU's plan to cut GHG emissions by at least 55 % by the year 2030 compared to 1990 levels. The EU aims to achieve a balance between greenhouse gases emitted and removed from the atmosphere to reduce its net emissions to zero by 2050 (European Commission, 2020a). The Commission launched the Farm to Fork strategy to stimulate sustainable food consumption and promote affordable healthy food for all, with additional measures taken to reduce

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https://doi.org/10.1016/j.spc.2024.08.031
Received 13 May 2024; Received in revised form 26 August 2024; Accepted 30 August 2024
Available online 19 September 2024

the use of pesticides by 50 % and fertilizers by at least 20 % by 2030 (European Commission, 2020b). The EU also seeks to reduce the environmental impact of the food system, enhance its resilience, and lead a global shift towards competitive sustainability in agriculture (European Commission, 2023). Likewise, The German Bioeconomy Council is also addressing this global protein challenge by recommending alternative protein sources, new agricultural systems for sustainable protein production, and the efficient use of by-products and residues (Lang et al., 2017).

In order to reach these ambitious climate targets, there is a growing recognition that emissions related to food sector must be significantly reduced (Clark et al., 2019). The analysis of various studies reveals that protein sourced from plant-based foods tends to have lower environmental impacts when compared to its animal-based counterparts (Clune et al., 2017; Röös et al., 2020; van Rysselberge and Röös, 2021). Plant-based protein sources, including legumes, grains, and vegetables, typically require less land, water, and energy for production, resulting in reduced GHG emissions and other environmental impact (Poore and Nemecek, 2018).

Wheatgrass (*Triticum aestivum*) in particular is one such protein sources, as it contains more protein per fresh weight (3.3 %) than other protein rich vegetables like spinach (2.9 %) and broccoli (2.6 %) (U.S. Department of Agriculture, 2019; Huft et al., 2023). Wheatgrass has also gained increased attention in recent years owing to its perceived potential health benefits. It is reported to be rich in various nutrients like proteins, minerals and vitamins (Devi et al., 2019; Eissa et al., 2020). Other advantages of wheatgrass are its wide availability and short growing time (6–14 days) (Cores Rodríguez et al., 2022; Patil et al., 2022). Derived from the young shoots of the wheat plant, it is commonly consumed as a juice or in powdered form (Patil et al., 2022).

Wheatgrass can be cultivated outdoors or indoors, but it is mostly cultivated indoors currently (Chakraborty et al., 2023). Indoor cultivation provides the possibility of regulating the antioxidant content by varying the photoperiod and wavelength of the exposed lights (Chalil et al., 2022). Indoor farming systems provide a controlled environment, which minimizes the vulnerability of crops to external factors such as weather fluctuations and natural disasters, thus securing a year-round production with higher yield (Pinstrup-Andersen, 2018). To further increase the wheatgrass production yield per base area, indoor farming is often combined with vertical farming (VF) systems, which promises more efficient resource utilization, less demand on water and land with maximum yields compared to conventional farming practices (Benke and Tomkins, 2017). Thanks to these potential advantages, vertical farming has attracted attention in recent years despite the very high initial investment and operating costs (Huebbers and Buyel, 2021). According to STATISTA data, the market size of VF has steadily increased and is expected to further expand to 23.7 billion US dollars by 2030 (STATISTA, 2023). The utilization of vertical farming technology for the indoor cultivation of wheatgrass presents a promising solution for addressing the dual challenges of sufficient protein supply and achieving climate target. Thus, this study aims to investigate the environmental impacts of wheatgrass protein produced in a novel vertical farming system using life cycle assessment (LCA) methods. Additionally, the LCA results for wheatgrass protein are compared with those of traditional protein sources to provide a comprehensive overview of its environmental performance. This comparison seeks to elucidate the relative environmental impact of wheatgrass protein. Furthermore, various scenarios are analyzed to assess the optimization potential of wheatgrass protein production.

2. Literature review

In recent years, vertical farming has already gained scientific interest, leading to increased research and publications. One of the focuses within this discourse is the sustainability of such systems. To evaluate the environmental sustainability, the life cycle assessment (LCA) methodology is usually applied, which is the most advanced method to evaluate the environmental impacts of a product, process, or activity throughout its entire life cycle (Göran Finnveden et al., 2009; Li et al., 2018).

On the one hand, studies claim that the vertical farming can be beneficial compared to conventional agriculture regarding environmental impact. Vertical farming can provide benefit in reducing land, water, pesticide and fertilizer demand thus delivering sustainable food (Stiles and Wootton-Beard, 2017; Oh and Lu, 2022). Studies focusing on the operation of vertical farms confirm these statements. For example, an aeroponic farm producing microgreens (pea shoots) in the UK offered lower impact food than equivalent imported food (Schmidt Rivera et al., 2023). Few studies (Tuomisto, 2019; van Gerrewey et al., 2022) suggest that the GHG emissions in vertical farms can be lowered by using nuclear or renewable energy instead of fossil-based energy (coal and gas). Finally, a vertical farm in Sweden producing lettuce was found to have lower GHG emissions than conventionally sourced varieties, which was attributed to the high share of renewable energy in Swedish electricity grid mix (Martin et al., 2023).

On the other hand, results on the contrary are also published regarding the environmental performance of vertical farms and indoor farming systems in general. The carbon footprint of lettuce produced in a vertical farm in the Netherlands was reported to be 5.6–16.7 times greater than that of the conventional farming (Blom et al., 2022). The GHG emissions of producing lettuce in a vertical farm can be higher than conventional agriculture due to the great electricity demand (Wildeman, 2020; Casey et al., 2022). Weidner et al. (2022), argue differently on the potential land-savings claims of VF, when the indirect land requirement for producing the electricity is also considered. They suggest that the performance of VF when compared with other agricultural practices differ across regions and no generalised recommendation can be given.

Though most studies highlight significant land and water saving potential of vertical farms compared to conventional cultivation techniques, the challenge of high energy consumption and the resulting potential environmental impact still remains. Furthermore, existing research is predominantly focused on a limited number of crops grown hydroponically and neglects alternative cultivation technologies such as aeroponics and other potential crops. Hence, despite the increasing scientific and commercial interest, the number of LCA studies on vertical farming is still limited and the lack of transparently published data by vertical farming companies make it difficult to further investigate the sustainability of this technology (Kalantari et al., 2018; Martin, 2023).

Our study addresses this research gap by assessing the environmental performance of a novel VF-technology, namely OrbiPlant® to produce wheatgrass as an alternative protein source. In doing so, this LCA study helps to identify the ecological hotspots of the investigated production system as well as optimization potential through scenario analysis.

3. Methodology

3.1. Goal and scope of the life cycle assessment

3.1.1. Goal

The objective of this study is to investigate the environmental performance of proteins extracted from wheatgrass produced within a novel vertical farming system. In order to understand the environmental performance of the product, its environmental impacts are compared with those of conventional animal-based proteins. In addition, various scenarios are investigated to identify optimization potentials for such a controlled environmental agriculture system along with the downstream processes for protein extraction.

To do so, the LCA was structured and conducted according to the ISO 14040:2006 and ISO 14044:2006 standards (DIN, 2021b, 2021a). The LCA was modelled using the software OpenLCA version 2.02 and follows an attributional approach.

In accordance with the goal of the study, the functional unit is related to the production of a certain amount of proteins. Due to the variability in protein content across different biomasses, the functional unit is specifically defined as 1 kg of crude protein, rather than referring to the 1 kg biomass.

3.1.2. System boundary

The geographical scope of this study is Germany, as the main technology under investigation is currently introduced to the German market. The system boundary is 'cradle-to-gate', so that the consumption and end of life (EoL) of the products (wheatgrass protein) are excluded from the assessment. However, the EoL of the vertical farming system as well as the handling of waste generated during the production are considered in the study. The production processes are divided into: (1) the construction and EoL of the system (a novel aeroponic vertical farm called OrbiPlant® with a meandering, rotating conveyor belt and plants directly growing in the conveyor belt, see Fig. S1 in Supplementary materials) (Vogel and Schillberg, 2023), (2) wheatgrass cultivation in the OrbiPlant®, and (3) the protein extraction processes (see Fig. 1).

All the buildings are excluded from the study, as the production is at pilot scale and the test facilities are still integrated within a pre-existing building. However, the OrbiPlant® system is included since one of the differences of vertical farms against traditional agriculture activities is the closed environment built on purpose. Besides, the storage of the harvested wheatgrass, transportation of the grass to protein extraction is also excluded, as the OrbiPlant® and the protein extraction is planned to be in the same building and the wheatgrass will be processed immediately after harvest. The packaging of the final product and its storage is excluded as well, as these process stages are not relevant for the research question.

3.1.3. Data collection

Primary data were during the soilless wheatgrass production at the Fraunhofer IME OrbiPlant® facility in the first half of 2023 under controlled environmental conditions (Vogel and Schillberg, 2017). The data for the protein extraction processes is based on the pilot-scale production and scaled up to a larger scale by the extraction technology developers. Secondary data was taken from the Ecoinvent cut-off database (Ecoinvent v. 3.91).

Cheese is employed as reference animal-based protein source to the proteins extracted from wheatgrass. Cheese was selected as reference animal-based protein since the emulsifying properties of wheatgrass protein powder was proved to be a suitable ingredient in bread spread that can substitute cheese. The Ecoinvent dataset "cheese production, soft, from cow milk" is used as the animal-based reference data set. Protein content of cheese is set to be 19.4 % according to database provided by Federal Food Safety and Veterinary Office (FSVO, 2023). In addition, soy protein was selected as reference since soybean is an important plant-based protein source to meet protein requirements in the Asian region and is also gaining interest in western hemisphere (Rizzo and Baroni, 2018; Qin et al., 2022). The dataset "Soy protein, textured, dehydrated, from soy flour, at plant" from Agribalyse is used as the plant-based reference (Colomb et al., 2015). Protein content of soy protein is 67 % according to the study behind the data set (Saerens et al., 2021). While we acknowledge the importance of comparing the results with other protein sources, our primary focus remains on investigating the environmental impact of wheatgrass protein produced using the novel OrbiPlant® technology. The comparisons made with cheese and soy protein are intended to offer an overview of the relative environmental performance of wheatgrass protein, rather than to provide an exhaustive comparison with other protein sources.

3.1.4. Handling multifunctionality

The way of handling multifunctional process is always a challenge in an LCA study and greatly influence the LCA result (Ciroth, 2021). The issue of multifunctionality occurs when a system produces multiple product outputs or uses inputs that originate from another product life cycle. In this study, wheatgrass protein concentrate powder is the main outcome of the production process. At the same time, grass root and the remaining grass stalks after harvesting are obtained as by-products. During the protein extraction processes press cakes are also produced as by-products.

The ISO standards 14040/44 offer a guideline to deal with the multifunctionality issue (DIN, 2021b, 2021a). The first recommendation is to avoid allocation by dividing the process into two or more subprocesses each with its own inputs and outputs or expanding the product system to include the avoided product. If allocation cannot be avoided, the standard recommends partitioning emissions based on a physical relationship; if no such relationship exists, allocation reflecting other relationships, like economic value, is recommended. For the studied case, dividing the process is not possible. The allocation based on the mass lacks a scientific justification as the by-product has a much lower nutritional and economic value. Economic allocation remains hard as well due to the uncertainty of the price of the products. Thus, the present study employs a substitution approach. Mass allocation is

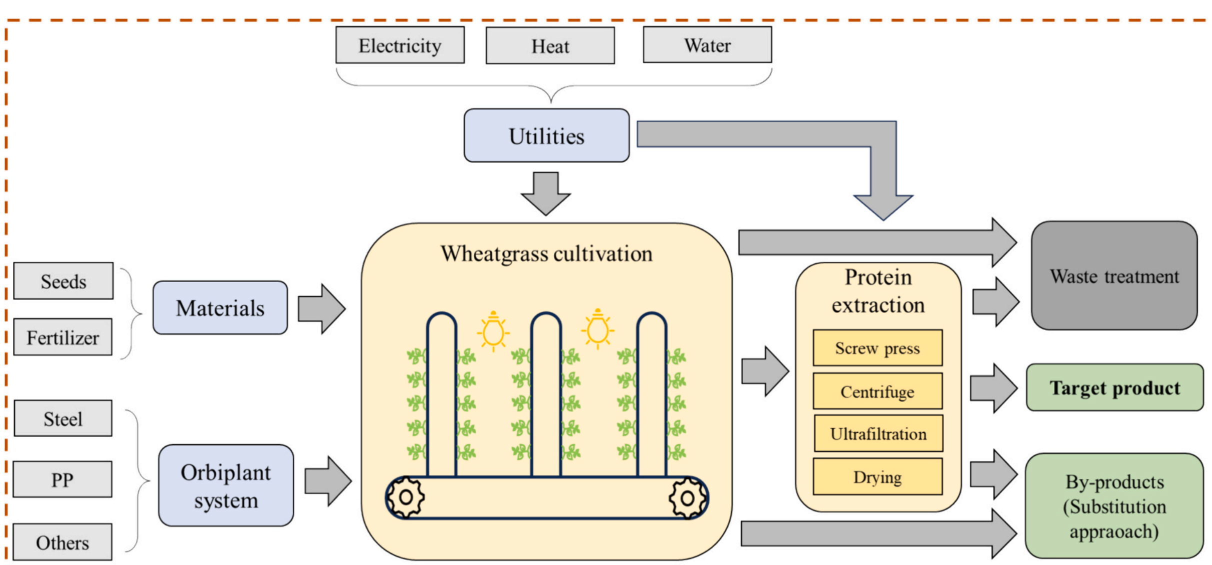

Fig. 1. System boundary of the investigated wheatgrass protein concentrate powder production system.

applied in a sensitivity analysis (see Section 4.3.2) to show the impact of methodological choices on the results.

The by-products are used to substitute grass silage as animal feed providing the same amount of protein, which is represented by the data set "grass silage production, Swiss integrated production, intensive" provided in the Ecoinvent database. The by-products substitute the mass of grass silage providing the same amount of protein. By-products contain 4 % protein according to the measurement and the grass silage contains 13.5 % protein according to the data set. The environmental impact of the substituted grass silage is considered as credit to produce the main product, thereby offsetting the environmental impact associated with the production of wheatgrass protein.

3.1.5. Impact assessment methodology

The Environmental Footprint v. 3.1 life cycle impact assessment (LCIA) method is applied in this study as it is developed by the European Commission (EC) and provides a robust method for investigating the environmental impact of the products in the European market (European Commission, 2013; Zampori and Pant, 2019). Thus, the environmental impact categories chosen are acidification (AC), climate change (CC), freshwater ecotoxicity (ETO), resource use fossils (RU_f), freshwater, marine and terrestrial eutrophication (EU_f, EU_m, EU_t), carcinogenic and non- carcinogenic human toxicity (HT_C, HT_{NC}), ionising radiation (IR), land use (LU), resource use for minerals and metals (RU_m), ozone depletion (OD), particulate matter (PM), photochemical ozone formation (POF), and finally water use (WU). The chosen impact category methods and their respective units are provided in supplementary materials (see Table S1).

To assess the trade-offs between different environmental impact categories, normalization and weighting was also applied to the results. The European JRC developed a method for weighting the Environmental Footprint Impact Categories according to their relevance for the overall environmental problems (Sala et al., 2018).

3.2. Systems under study and life cycle inventories

3.2.1. Baseline scenario

The baseline scenario is based on the resource and energy consumption data collected from the pilot scale OrbiPlant® facilities and protein extraction process. The OrbiPlant® system operates with a conveyor belt system on which wheatgrass is cultivated using aeroponic technology (Huebbers and Buyel, 2021). The innovative OrbiPlant® system features several improvements over current VF systems, including higher biomass yields, shorter growth cycles, improved vertical heat convection, simplified logistics and reduced light emitting diodes (LED) lighting requirements (Baldock, 2019). Mechanical extraction and cascaded ultrafiltration are used to fractionate plant proteins from wheatgrass. The details on the assumptions and modelling employed in the baseline scenario are provided in the following sections.

OrbiPlant® system to create the cultivation environment is one of the significant differences between VF and traditional farming. Accordingly, the main material demand for the equipment is included in the LCA. The pilot scale OrbiPlant® system has a total gross cultivation area of 45 m^2. The material demand is driven by the construction of OrbiPlant® frame, the supporting structures and the aeroponic system, which mainly includes stainless steel, aluminium, and polypropylene (PP). Due to minor relevance and lack of reliable data, the manufacturing processes are simplified by using Ecoinvent data sets which include the co-extrusion of PP and impact extrusion of the stainless steel and aluminium. Besides, main components to build the cultivation area are simplified to air conditioner, LEDs, pumps, and the control unit and existing Ecoinvent data sets are used for modelling these. The expected lifespan of all materials and components, as well as the used background datasets is shown in Table 1. We assume that the same mass of these materials and the wastewater produced must be taken into account in the EoL phase.

Besides, materials at the EoL and chosen datasets for waste treatment are presented in the table, too. A 10-kW air conditioner is required, but the available dataset only includes devices with a capacity of 100 kW. The dataset is scaled-down linear, using 0.1 unit of the device to represent a 10-kW device. The used air conditioner, LEDs and control units are classified as waste electronics. Besides, the pumps after lifespan are disposed as waste steel.

Base scenario uses the data collected from the pilot scale OrbiPlant® system. Currently, CO_2 enrichment of the cultivation environment is not implemented in the OrbiPlant®. The aeroponic OrbiPlant® system uses a novel vertical farming approach to produce plant biomass directly in a vertically meandering conveyor belt and is integrated into the existing Fraunhofer IME building without exposure to sunlight (Vogel and Schillberg, 2017). The entire facility is driven by electrical energy. Wheatgrass seed material was sourced from KWS SAAT SE & Co. KGaA, Einbeck, Germany. The materials and utilities used were measured within a 3-harvest cultivation cycle, which starts from a 2-day seed pre-

Table 1
Data used for OrbiPlant® system.

Category	Mass or energy flow	Amount	Unit	Life expectancy (years)	Ecoinvent dataset
Input flow					
OrbiPlant®	Stainless steel	571.2	kg	30	GLO: market for steel, chromium steel 18/8
	Manufacturing process of stainless steel	571.2	kg		GLO: market for impact extrusion of steel, cold, 2 strokes
	Aluminium	1060.8	kg	30	IAI Area, EU27 & EFTA: market for aluminium, primary, ingot
	Manufacturing process of aluminium	1060.8	kg		GLO: market for impact extrusion of aluminium, 2 strokes
	Polypropylene (PP)	198	kg	10	GLO: market for polypropylene, granulate | polypropylene, granulate
	Manufacturing process of PP	198	kg		GLO: market for extrusion, co-extrusion
	Control unit	1	piece	8	EU: electronics production, for control units
	Air conditioner	0.1	piece	20	GLO: market for absorption chiller, 100 kW
	LED	2352	unit	8	GLO: market for light emitting diode
Aeroponic system	Steel	174.2	kg	30	GLO: market for steel, chromium steel 18/8
	Manufacturing process of stainless steel	174.2	kg		GLO: market for impact extrusion of steel, cold, 2 strokes
	Polypropylene (PP)	49	kg	10	GLO: market for polypropylene, granulate
	Manufacturing process of PP	49	kg		GLO: market for extrusion, co-extrusion
	Pumps	2	piece	8	GLO: market for pump, 40 W
Output flow					
Product	OrbiPlant® facility	1	Unit		
End of Life	Waste steel	763.6	kg		Europe without Switzerland: market for scrap steel
	Waste aluminium	1060.8	kg		GLO: market for waste aluminium
	Waste PP	594	kg		DE: market for waste polypropylene | waste polypropylene
	Waste electronics	239.3	kg		GLO: market for waste electric and electronic equipment

treatment (swelling and pre-germination). The pre-treated seeds were then applied onto mesh-like recesses of conveyor belt segments for full germination and root development. After a germination period of 3 days the conveyor belt segments with the fully germinated wheatgrass seeds were then slotted into the vertical OrbiPlant® system to start the 3-harvest wheatgrass cultivation cycle. The first wheatgrass harvest cut took place after 6 cultivation days in the OrbiPlant® system and multiple harvests cuts every 6 days are possible. After the 3rd harvest cut the roots and the remaining stalks of the wheatgrass were harvested together the green wheatgrass biomass, as the growth rate of the wheatgrass decreases with increasing harvest cuts. The current OrbiPlant® pilot scale system has a cultivation area of ~45 m^2 and yields 3.3 t wet biomass (without roots and stalks) per year. Lighting, heating, ventilation, and air conditioning (HVAC) system contribute most to the energy demand. 80 % of the water used in the aeroponic system is condensed and recycled, while the water used for cleaning is completely disposed. The data for the wheat seeds, wheatgrass biomass, roots and remaining stalks (see Table 2) were collected as fresh weights with a laboratory scale. The amount of NPK fertilizer and phosphoric acid used during a cultivation cycle was read in ml in the corresponding storage containers of the OrbiPlant® stock solution. The electricity consumption for lighting, conveyor belt motor, fluid pumps, HVAC and harvesting device was calculated as kWh based on the corresponding power specifications and running times. The quantity of water used during cultivation was measured with a water meter. Wastewater produced per cultivation cycle was calculated based on the water flow rate and running time.

Potential emissions of NH_3, N_2O or other trace gases during production have not been measured but are considered unlikely due to the closed cultivation system design.

The measured quantities of materials and utilities are scaled to 1 kg of wheatgrass and are shown in Table 2.

Protein extraction as defined in the base scenario is based on pilot scale data. The data are scaled-up to a throughput of 1000 kg fresh wheatgrass per hour.

The process started with washing the harvested biomass. As the crop was cultivated with aeroponic techniques in a controlled environmental agriculture system, they are free from contamination and soils and thus need little amount of water for washing. The cleaned crop passed through a screw press, where the liquid was separated from the solid content. The liquid phase leaving the screw press was called green juice and was transferred to a centrifuge. The green juice was centrifuged for a short time depending on the residual solid phase. The pure liquid green juice was then forwarded to a membrane system for protein concentration. The membrane unit consists of two parts, the microfiltration and ultrafiltration. The protein concentrates after ultrafiltration can reach up to 40 %. The final step of the processes was the evaporation of the residual water content in the protein concentrate with a spray dryer. The product out of the whole protein extraction process was wheatgrass protein concentrate powder, which contains up to 68 % of protein. The press cake from screw press and pellet from centrifuge were considered as by-products, while the permeate from the filtration units can only be disposed as wastewater.

The materials and energy demand for producing 1 kg protein concentrate powder are shown in Table 3.

3.2.2. *Overview on optimization scenarios*

As the novel vertical farming technology is still under development and only at small pilot-scale, there is a lot of potential for improvement. The investigated optimization scenarios are presented in Table 4, wherein scenario S1 evaluates the influence of higher wheatgrass yields and higher protein extraction efficiencies achieved by optimizing the production system. Scenario S2 explores the improvement in energy efficiency. Scenario S3 is a combination of Scenario S1 and Scenario S2, which investigates the technical improvement potential without switching the electricity source. Scenario S4 analyses the effect of switching to renewable power. Finally, Scenario S5 combines all the improvements from the scenarios S3 and S4 to represent the best case. Details on the scenarios can be found in the following sub-sections.

3.2.3. *Scenario S1: improved production efficiency*

Scenario S1 evaluates the influence of improving the wheatgrass

Table 2
Data used for cultivation of 1 kg wheatgrass biomass. HVAC: heating, ventilation, and air conditioning.

Category	Mass or energy flow	Amount	Unit	Ecoinvent dataset
Input flow				
Seed and Fertilizer	Wheat seed	0.31	kg	DE: wheat production | wheat grain
	NPK-fertilizer	0.033	kg	EU: market for NPK (26-15-15) fertilizer
	Phosphoric acid	1.27e−5	kg	EU: market for phosphoric acid, fertilizer grade, without water, in 70 % solution state
Utilities	Electricity, lighting	6.33	kWh	DE: market for electricity, low voltage
	Electricity, HVAC	1.69	kWh	DE: market for electricity, low voltage
	Electricity, other operation	0.37	kWh	DE: market for electricity, low voltage
	Water	9.62	kg	EU: market for tap water
Output flow				
Product and by-product	Wheatgrass biomass	1	kg	
	Root and remaining stalks	0.59	kg	
End of Life	Wastewater	4.5	kg	EU: market for wastewater, average

Table 3
Data used for the extraction of 1 kg protein concentrate powder.

Category or process	Mass or energy flow	Amount	Unit	Ecoinvent dataset
Input flow				
Biomass	Wheatgrass biomass	67.39	kg	
Wash	Electricity	0.067	kWh	DE: market for electricity, low voltage
	Water	67.39	kg	EU: market for tap water
Press	Electricity	1.62	kWh	DE: market for electricity, low voltage
	Water	6.74	kg	EU: market for tap water
Centrifuge	Electricity	0.069	kWh	DE: market for electricity, low voltage
Ultrafiltration	Electricity	0.37	kWh	DE: market for electricity, low voltage
Drying	Heat	2.7	kWh	EU: market group for heat, central or small-scale, natural gas
Press cake treatment	Heat	17.18	kWh	EU: market group for heat, central or small-scale, natural gas
Output flow				
Product and by-product	Protein concentrate powder	1	kg	
	Press cake	5.23	kg	
End of Life	Permeate	41.66	kg	EU: market for wastewater, average

Table 4
Investigated scenarios for wheatgrass protein concentrate powder production. HVAC: Heating, Ventilation, and Air Conditioning; COP: Coefficient of Performance.

Scenarios	Name	Improvement
BS	Base case	Current pilot-scale measurements
S1	Production efficiency	More wheatgrass per cultivation +60 % & Improved extraction rate +20 %
S2	Energy efficiency	Reduced energy consumption through lighting −35 % 50 % of the energy in HVAC system use passive cooling with a COP of 20
S3	Efficiency improvement	Product + Energy Efficiency
S4	Energy source	Renewable energy source (Wind power in Germany)
S5	Best case	Integrate S3 and S4

yield and protein extraction efficiency on the overall environmental performance. The yield can be maximized by optimizing the crop-growing conditions, for example through accurate lighting control and optimized lighting spectra, fine-tuning temperature and humidity and precise fertilizer supply (Islam et al., 2021; Farhangi et al., 2023). A relative humidity of 50–90 % is ideal for most plants grown a vertical farm (Rabbi et al., 2019). According to the OrbiPlant® operator, 60–70 % is the optimal humidity for wheatgrass. Besides, the proper distribution of air is also important to the growth (Wildeman, 2020). The production of wheatgrass is done currently on the pilot scale OrbiPlant® system, which still stands in the middle of its optimization both on design and operation. This means the growing condition for wheatgrass can be further improved.

Another improvement potential is to increase the cultivation area of the conveyor belt in the OrbiPlant®. In the current design, a large part of the conveyor belt surface is used to support the stability required to move the conveyor, as such only 40 % of the total surface is used. By improving the design of the conveyor belt the useable area can be increased by up to 60 %, which results in 60 % higher yield despite the same use of resources and energy. Based on the estimation of the OrbiPlant® developers, an increase in yield of 70 % is possible, while the input of materials and energy stay at the same level as current operation. It would be rather a conservative estimation considering the low Technology Readiness Level (TRL) of the OrbiPlant® technology.

In the case of protein extraction, it is also expected that not only the energy requirement for extraction, but also the protein yield of the process can be increased. The estimation of increasing efficiency is based on discussions with developers of the wheatgrass protein extraction technology. It is estimated that the process yield can be increased by 20 %.

3.2.4. *Scenario S2: improved energy efficiency*

Scenario S2 aims to investigate the environmental benefits of improving the energy efficiency of the OrbiPlant® operation. Energy is mainly used to distribute light energy to plants and later extract that energy as heat using HVAC systems. (van Delden et al., 2021). Light in vertical farms is mostly provided by artificial lighting system, and electricity used in lighting system contributed mostly to the total energy consumption (Lubna et al., 2022). It can be observed in various studies, that the lighting system uses up to 74 % of the total electricity demand (Barge, 2020; Wildeman, 2020; Blom et al., 2022).

LEDs are used in most vertical farms, as it offers several advantages compared to traditional lighting methods, such as higher energy efficiency, longer lifespan and better durability (Morgan Pattison et al., 2018). Over the last 15 years, the efficiency of cool white LED packages have improved from around 25 lm W^{-1} (lumens per watt) to over 160 lm W^{-1}, which equals to 540 % improvement and the cost keep decreasing so that it is competitive with the traditional lighting products (Morgan Pattison et al., 2018). The LED used in the current OrbiPlant® are rather an old model produced in 2014. In view of the rapid development of LED technologies, there is great energy-saving potential for an upgraded lighting system in the OrbiPlant®.

It is assumed that in the scenario with improved energy efficiency, 35 % less electricity is needed for the LED system to provide the same lighting intensity. The improvement in lighting benefits the HVAC system as well, which is the other large energy consumer in vertical farms. According to (Yu et al., 2023) up to 80 % of the electricity feed to LED ends as heat loss. As a result of increased LED efficiency, the cooling demand in VF is correspondingly decreasing.

Currently, the HVAC was totally carried out by the centralized system combined with the rest of the building, which will be optimized during further development of the technology. It is also planned to integrate natural ventilation with the HVAC for cooling down. According to the local weather data, it can be assumed that half of the time in a year, the air outside is cooler and can be used both for ventilation and cooling. As such natural ventilation system can reach a coefficient of performance (COP) of 20 and thus greatly save the total energy required for cooling (Kaup et al., 2019; Rabbi et al., 2019).

3.2.5. *Scenario S3: improved production and energy efficiency*

Scenario S3 combines the efficiency improvement both in production and energy optimization, so that the environmental performance of the wheatgrass protein after upscaling and optimization using current energy source can be assessed. It could be considered as the realistic scenario, that can be achieved without large effort of changing the macro conditions like the location and local electricity mix.

3.2.6. *Scenario S4: renewable energy sources*

Studies show that vertical farms can have a much larger carbon footprint unless the electricity used comes from renewable energy or nuclear power plants (Al-Chalabi, 2015). It is therefore worth investigating the impact on the environment by switching fully to renewable energies. Wind power is used for this study, as it is the most important renewable energy source in the German electricity mix. Scenario S4 keeps the same inventories as baseline scenario and only change is the electricity source to wind power.

3.2.7. *Scenario S5: best case scenario*

A best-case scenario is created combining of all the improvement mentioned above to see the potential of the wheatgrass protein production. The change of the inventories in different scenarios can be seen in the following Table 5. Scenario S4 has all the inventories as base case, while only changing the energy source. Scenario S5 has the inventories as scenario S3, and renewable energy sources as well.

Table 5
Overview of the inventories changed in scenarios. BS: baseline scenario; S1: Scenario 1 production efficiency; S2: Scenario 2 energy efficiency; S3: Scenario 3 efficiency improvement; HVAC: Heating, Ventilation, and Air Conditioning.

Mass/energy flow or process	BS	S1	S2	S3	Unit
Electricity lighting	6.33	3.96	4.12	2.57	kWh/kg biomass output
Electricity HVAC	1.69	1.06	1.1	0.69	kWh/kg biomass output
Root and remaining stalks	0.59	0.37	0.59	0.37	kg/kg biomass output
Wheatgrass biomass	67.4	56.2	67.4	56.2	kg/kg powder output

4. Results and discussion

4.1. Environmental impacts of base scenario

4.1.1. Climate change

All the results are presented in the whole Section 4 in the form of a graph for better readability, while all LCIA results are available in figures in Tables S2 to S9 in the Supplementary materials.

For the impact category climate change, Fig. 2 shows the Global Warming Potential (GWP) associated with the production of 1 kg protein from wheatgrass protein concentrate powder. In total 417.6 kg CO_2-eq. are emitted during the production of 1 kg protein, while the credit gained from the by-products is quite low at only 5 kg CO_2-eq. A significant part of the GWP, around 87 %, is attributed to electricity consumption. Within this category, 67 % is attributed to LED consumption, 18 % to HVAC consumption and the remaining 3 % to other consumption (aeroponic system and conveyor belt). The impact of seeds production is greater than that of nutrients, although it remains relatively small compared to the emissions from electricity consumption. The downstream process has only a minor impact, accounting for less than 2.3 % of total emissions. OrbiPlant® system in particular still plays an important role with 27 kg of CO_2 emissions, which should decrease as the system is scaled up and yields increase.

4.1.2. Other impact categories

Fig. 3 provides a contribution analysis of all investigated impact categories. Across all impact categories, utilities, especially electricity, contribute the most to the impacts with the exception of land use and water use.

It is worth noting that the impact of the seeds is significant in land use. Besides, the seeds also contribute to the EU_M, EU_T, PM and WU relatively much. While it is possible to reduce the impact from the seeds by extending the harvest time for a single sowing, under current conditions the reduced yield after three harvest outweighs the benefits of saving seed. The by-products (wheatgrass roots and press cakes from downstream processes) substitute grass silage used as animal feed leading to environmental benefits. The credits for the by-products have a positive effect on the reduction of AC, EU_t, LU, and PM. The OrbiPlant® system has a notable contribution to AC, EU_t, OD, POF, RU_m, HT_C and HT_{nc}. This is caused by the demand for steel and aluminium required for construction.

4.2. Environmental impacts of optimization scenarios

4.2.1. Comparison of climate change with conventional protein sources

The GWP of all scenarios and contribution from different production steps are shown in Fig. 4. The GWP of soy protein is 1.7 kg CO_2-eq. FU^{-1}, which is much lower than both wheatgrass and cheese protein. Soy protein is generally considered a sustainable source of protein, as a result of high protein content in soybean and the fact that fewer resources are required for its cultivation than for the rearing of animals. The soy protein considered in this study is based on a by-product from soybean oil production, which also makes it less environmentally impactful than the investigated wheatgrass protein from the VF system. Given that soy protein demonstrates significantly lower impacts across all categories, it is excluded from further interpretation as further analysis is deemed unnecessary.

In the following section comparison is made between wheatgrass protein and cheese as reference. In scenario S1 the GWP is halved compared to the baseline scenario by increasing the production efficiency resulting in 207.3 kg CO_2-eq. FU^{-1}. As shown in scenario S2, improvements in LED efficiency reduce the GWP to 294.3 kg CO_2-eq. FU^{-1}. Scenario S3 shows that the combined effect of S1 and S2 results in a reduced GWP of 146.8 kg CO_2-eq. FU^{-1}, while still being 1.8 times higher than when using 100 % wind energy as assumed in scenario S4. The switch to renewables (S4) significantly reduces the GWP to 80.9 kg CO_2-eq. FU^{-1}.

However, with 100 % wind energy, the relative impact of OrbiPlant® system becomes relevant contributing to 30 % of the GWP. In this case the provision of seeds is responsible for 20 % of the total GWP. These findings underline the need for additional improvements regarding biomass yield and OrbiPlant® system. When combining all improvements as done in scenario S5, the GWP can be reduced to 37 kg CO_2-eq. Under this scenario, further improvements should focus on farming strategies, such as modified sowing and harvesting methods to minimize the impact of seed production. The best-case scenario shows a

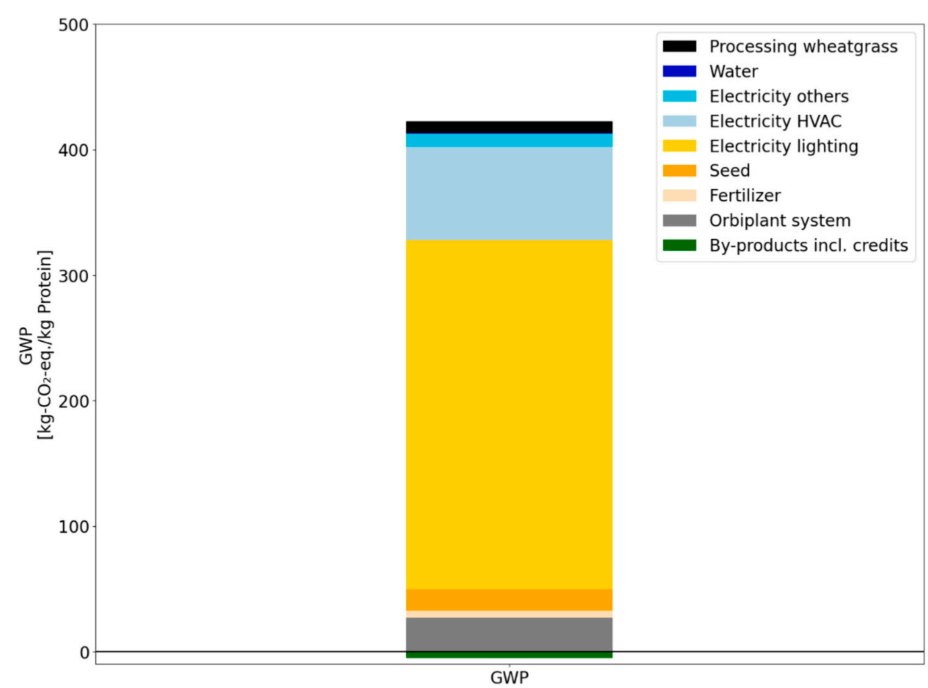

Fig. 2. Global warming potential (GWP) of producing 1 kg of wheatgrass protein concentrate powder (base case). HVAC: Heating, Ventilation, and Air Conditioning.

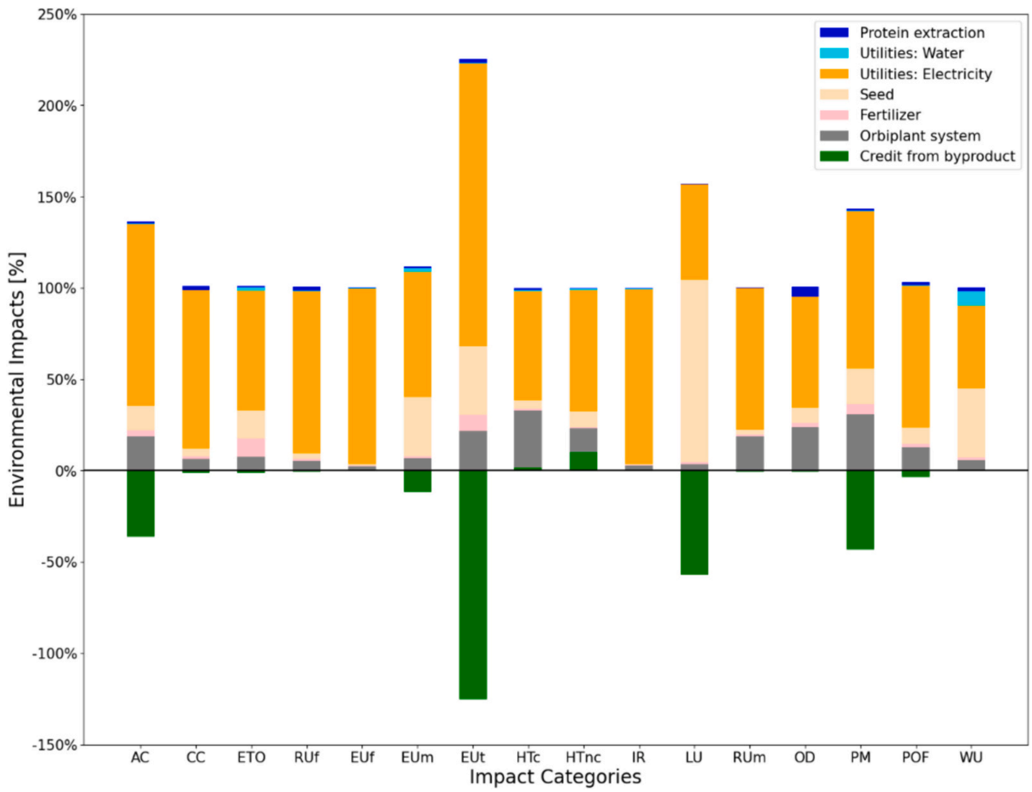

Fig. 3. Contribution analysis: all impact categories of producing 1 kg of wheatgrass protein concentrate powder (base case). AC: Acidification; CC: Climate Change – total; ETO: Ecotoxicity, freshwater; RU_f: Resource use, fossils; EU_f: Eutrophication, freshwater; EU_m: Eutrophication, marine; EU_t: Eutrophication, terrestrial; Human toxicity carcinogenic HT_c; Human toxicity non-carcinogenic HT_{nc}; IR: Ionising radiation; LU: Land Use; RU_m: Resource use, mineral and metals; OD: Ozone depletion; PM: Particulate matter; POF: Photochemical ozone formation; WU: Water use.

remarkably low impact, clearly below the reference value of cheese protein, indicating the great potential of wheatgrass as a sustainable protein source.

4.2.2. Comparison of all impact categories with conventional protein sources

As mentioned in section, soy protein shows much lower impacts than cheese and wheatgrass. It can be seen in Fig. 5, that the lower limits of the reference scenarios are all close to 0. Similarly, the discussion in this section is also based on the comparison with cheese as reference.

When looking into the production of cheese (upper limit of the reference scenario), lower environmental impacts in RU_f, EU_f, HT_c, HT_{nc}, IR, OD, RU_m and RU_f compared to all investigated wheatgrass scenarios can be observed. However, as shown in Fig. 5, impacts are comparatively high for EU_t and LU which are attributable to the associated livestock farming.

All scenarios including the baseline show considerable advantages in terms of land use, which confirms the advantage of vertical farms to use as little land as possible. The comparatively high eutrophication of cheese production is primarily due to the feed used to raise the animals, which requires the use of pesticides and herbicides for cultivation. Additionally, the management of animal waste contributes to both ecotoxicity and terrestrial eutrophication as well (FAO, 2004; Hristov et al., 2011). All scenarios of wheatgrass protein besides BS shows lower impacts on freshwater ecotoxicity than cheese protein, indicating that the wheatgrass protein have large potential on reducing the ecotoxicity with some improvement in the current production system. The reference system has a much higher impact on terrestrial eutrophication compared with wheatgrass protein. Wheatgrass protein under scenarios S4 and S5 even show negative values, which is due to the lower impact of production compared to the credits generated by the by-products substituting grass silage production. The fact that VF production has low impact on the environment can be explained by less fertilizer, pesticides or herbicides released to the environment. Surprisingly, savings in water use are not clearly observed for VF, as water consumption is strongly linked to energy consumption. Besides, the water use related to seed production and on-site water used for aeroponic system and cleaning is also not negligible.

In the best-case scenario S5, most impact categories show lower impacts compared to the cheese. However, it is also observed that even under best-case scenario, wheatgrass protein has much higher impacts in HT_c, HT_{nc}, RU_m and OD. Individual improvements in energy efficiency or productivity generally do not lead to a clear advantage over switching to 100 % wind energy. However, the combination of improvements already shows a better performance than 100 % wind energy in the impact categories of AC, ETO, EU_m, HT_c, HT_{nc}, LU, RU_m, OD, PM, POF and WU.

Normalization and weighting are applied to get insights into the overall performance of the investigated system. Since the result for soy protein as a reference is much lower and cannot be seen in the figure, comparisons between wheatgrass and cheese are provided in this subsection. The comparison of the aggregated results of the scenarios is shown in Fig. 6. Scenarios S3 and S4 have impacts at the same level and show that improvements in energy and production efficiency can achieve the same reduction in environmental impacts as switching to 100 % wind energy. Furthermore, the differences between these both scenarios and reference case are no longer evident, showing that wheatgrass protein will be comparable with cheese protein, if the current production could be improved in yield and energy efficiency or using renewable energy sources.

If the electricity source is switched to wind power, there will be a shift in most relevant impact categories. RU_m becomes the most important impact for scenarios S4 and S5 and thus differs from the other scenarios in which climate change dominates the overall impacts. In the

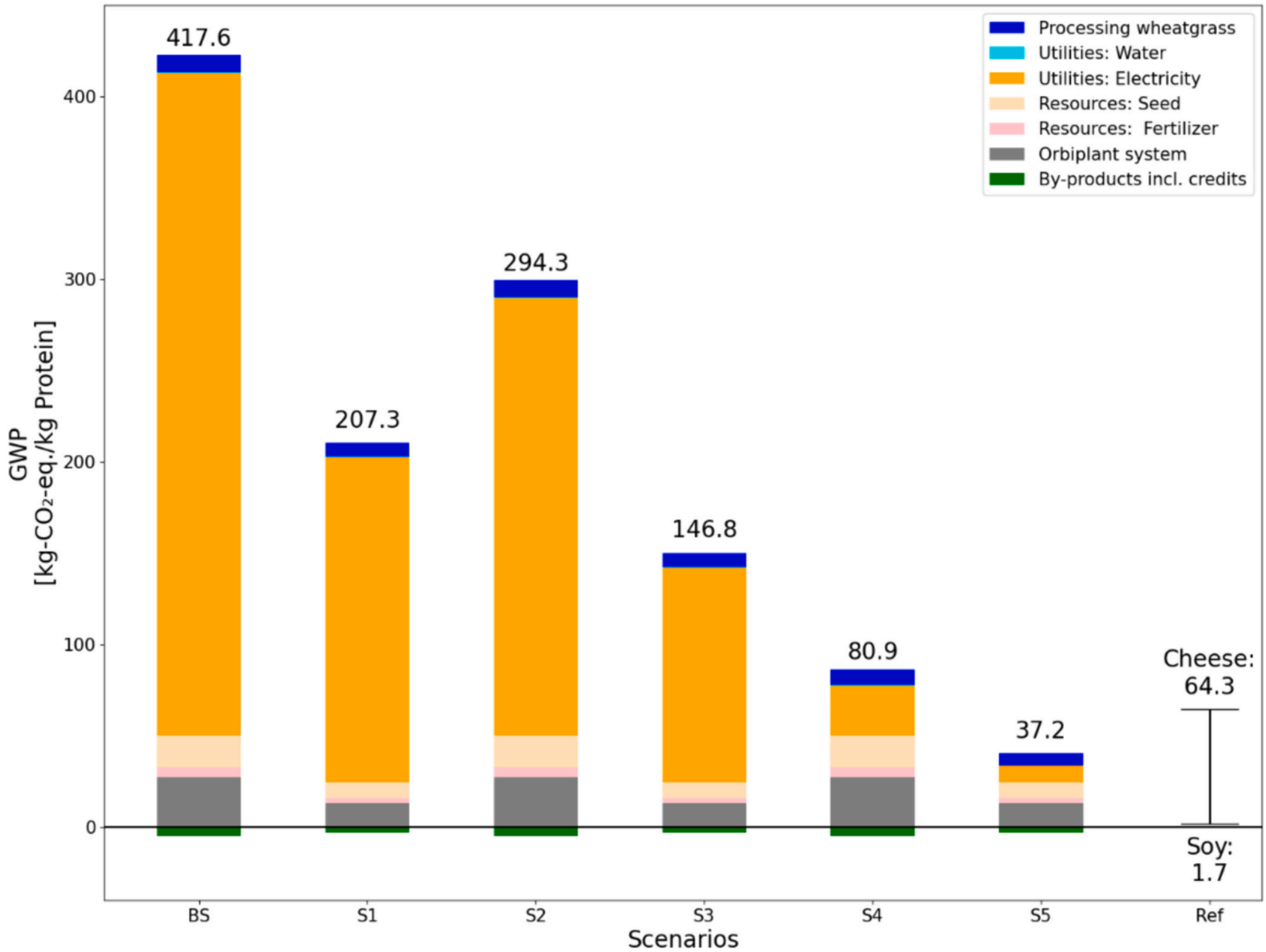

Fig. 4. Contribution analysis: GWP of producing 1 kg of wheatgrass protein concentrate powder (all scenarios). BS: base case scenario; S1: Scenario 1 production efficiency; S2: Scenario 2 energy efficiency; S3: Scenario 3 efficiency improvement; S4: Scenario 4 energy source; S5: Scenario 5 best case; Ref.: reference.

best-case scenario, the total environmental impact is less than 50 % of the reference value, which indicates the great potential of wheatgrass to reduce the environmental impact.

4.3. Sensitivity analysis

4.3.1. Sensitivity to energy efficiency and yield of wheatgrass

As shown in the scenario analysis, improvement in LED efficiency and yield of the crops can effectively reduce the environmental impact. The sensitivity of these two parameters on the total aggregate impacts is investigated in this part. To analyse the impact of LED efficiency on the environmental impact, a reduction in energy consumption of up to 90 % is assumed. Improvement in energy efficiency is varied by increments of 10 %. The biomass yield enhancement is varied from 0 % to 200 % in increments of 20 %. The environmental footprint of the reference system is used as benchmark to assess how much improvement is needed to make the wheatgrass protein more sustainable. The findings are illustrated in Fig. 7. All curves are above the reference line of soy protein, which indicates that the applied improvement does not make wheatgrass protein environmentally competitive against soy protein. It is noteworthy that the curve in the diagram shows a tendency of decreasing steepness when the LED efficiency increases. If the reduction in power consumption by LEDs is below 30 % (line red triangles), the environmental impact remains consistently above the reference value for cheese. Specifically for the power consumption of LEDs, it is shown that the environmental impact is above that of the cheese as reference system, even if the power consumption of LEDs is reduced by 90 %. For the environmental impact to be comparable to that of the cheese as reference system, improvements in production efficiency of 100 % and 200 % must be accompanied by a corresponding reduction in LED electricity consumption of at least 70 % and 40 % respectively.

4.3.2. Sensitivity on dealing with multifunctionality

Mass allocation is used to examine the effects of the different methods for considering multifunctionality on the results of the environmental assessment. Fig. 8 shows a comparison between the mass allocation and the substitution approach.

The cultivation of 1 kg wheatgrass biomass generates 0.59 kg of wheatgrass roots. During the protein extraction process, 5.23 kg of press cake is generated as byproduct along with 1 kg of protein concentrate powder. In the mass allocation method, 37 % of the environmental impact for wheatgrass cultivation is allocated to wheatgrass root and remaining stalks and 84 % of the environmental impact for protein extraction process is allocated to press cakes.

As can be seen from Fig. 8, the choice of allocation method has a significant influence on the results. In particular, the total environmental impact calculated using the mass allocation method is 35.6 % lower than that calculated using the substitution approach. However, as explained in the relevant section, the by-products in this study have a lower economic value than the main product. Therefore, we are of the opinion that the substitution approach is more appropriate for this study. The use of mass allocation here is merely to illustrate the impact

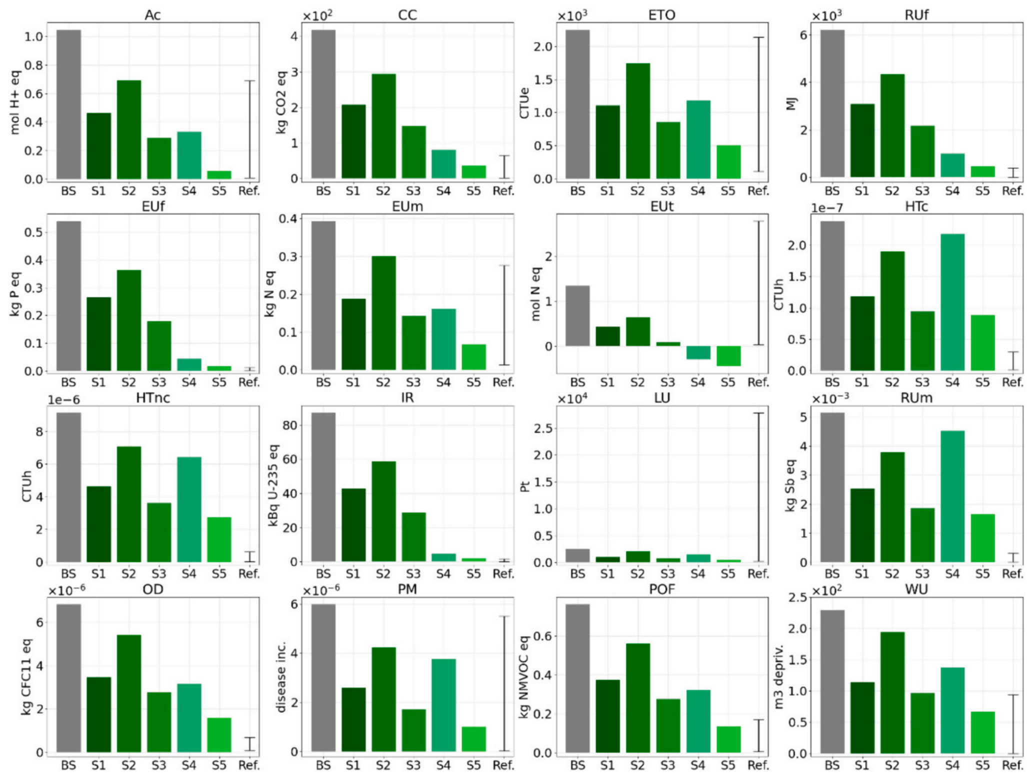

Fig. 5. All impact categories of producing 1 kg of wheatgrass protein concentrate powder (all scenarios). AC: Acidification; CC: Climate Change – total; ETO: Ecotoxicity, freshwater; RU_f: Resource use, fossils; EU_f: Eutrophication, freshwater; EU_m: Eutrophication, marine; EU_t: Eutrophication, terrestrial; Human toxicity carcinogenic HT_c; Human toxicity non-carcinogenic HT_{nc}; IR: Ionising radiation; LU: Land Use; RU_m: Resource use, mineral and metals; OD: Ozone depletion; PM: Particulate matter; POF: Photochemical ozone formation; WU: Water use; BS: base case scenario; S1: Scenario 1 production efficiency; S2: Scenario 2 energy efficiency; S3: Scenario 3 efficiency improvement; S4: Scenario 4 energy source; S5: Scenario 5 best case; Ref.: reference (upper limit is cheese and lower limit is soy protein).

of methodological choices on the results.

4.4. *Limitation of the study*

4.4.1. *Influence of the protein quality*

Besides the quantity, quality of protein varies across different protein source as well. Plant-based protein sources are often considered lower in quality as certain amino acids may be present in lower amounts or may have lower digestibility compared to animal-based proteins (Hertzler et al., 2020). The protein quality can be considered for the LCA study as well by using a digestible indispensable amino acid score (DIAAS) corrected FU (Sonesson et al., 2017; Berardy et al., 2019). However, its application in the presented study is limited due to a lack of data on the digestibility of wheatgrass protein concentrate powder. The amino acid profile of wheatgrass shows that lysin is the limiting amino acid, which is likely leading to a low DIAAS (Kaur et al., 2021). The environmental impacts of wheatgrass protein are thus expected to be higher if the protein quality is considered.

There is also the possibility to overcome this disadvantage by mixing wheatgrass protein with other plant-based protein sources. For e.g., the combination of wheatgrass and potato protein can realize a full amino acid profile. The consideration of protein quality into the LCA will be the focus of future investigations.

4.4.2. *Regional differences in life cycle impact assessment*

The Ecoinvent database used in this study does not specify the elementary flows regionally, which may lead to unprecise results in some impact categories (AC, PM, EU_m, EU_t, LU and WU). For example, the water scarcity in different region is not considered in water use category. All the water flows used as resource and emission share the same characterisation factor (CF) of 42.95. The comparison of the results with the reference remains reliable since the same CFs are used. However, the impact category water use may be overlooked in Germany where the production occurs, as the water scarcity in Germany is not severe and the water use CF is lower than the valued 42.95.

Although EF method provides regionalized CF for the impact categories mentioned above, Ecoinvent has not implemented the full CFs in their datasets and LCIA methods. Therefore, environmental impacts are still not regionalized in this study.

5. Conclusions

This paper investigated for the first time the environmental impacts of wheatgrass protein produced in a novel VF system. The scope of the LCA is ‘cradle-to-gate’ and the FU is 1 kg of crude protein. The LCA was performed using OpenLCA software and followed Environment Footprint 3.1 as LCIA methods. Soy and cheese protein are used as reference for comparison as representative animal-based and plan-based conventional sources.

The results show that soy protein shows much lower environmental impacts across all impact categories compared to cheese and wheatgrass protein, while wheatgrass protein from the novel VF has lower environmental impacts in categories EU_T and LU compared to cheese protein. Considering the overall environmental performance, the wheatgrass protein is still not competitive, showing above four times higher result in the normalized and weighted impact than cheese protein. The reason of the higher impact mainly goes to the large electric energy demand for the lighting and HVAC system and the relatively high environmental impact of the electricity mix in Germany. Although the target crop wheatgrass is already rich in protein as a plant, large amount

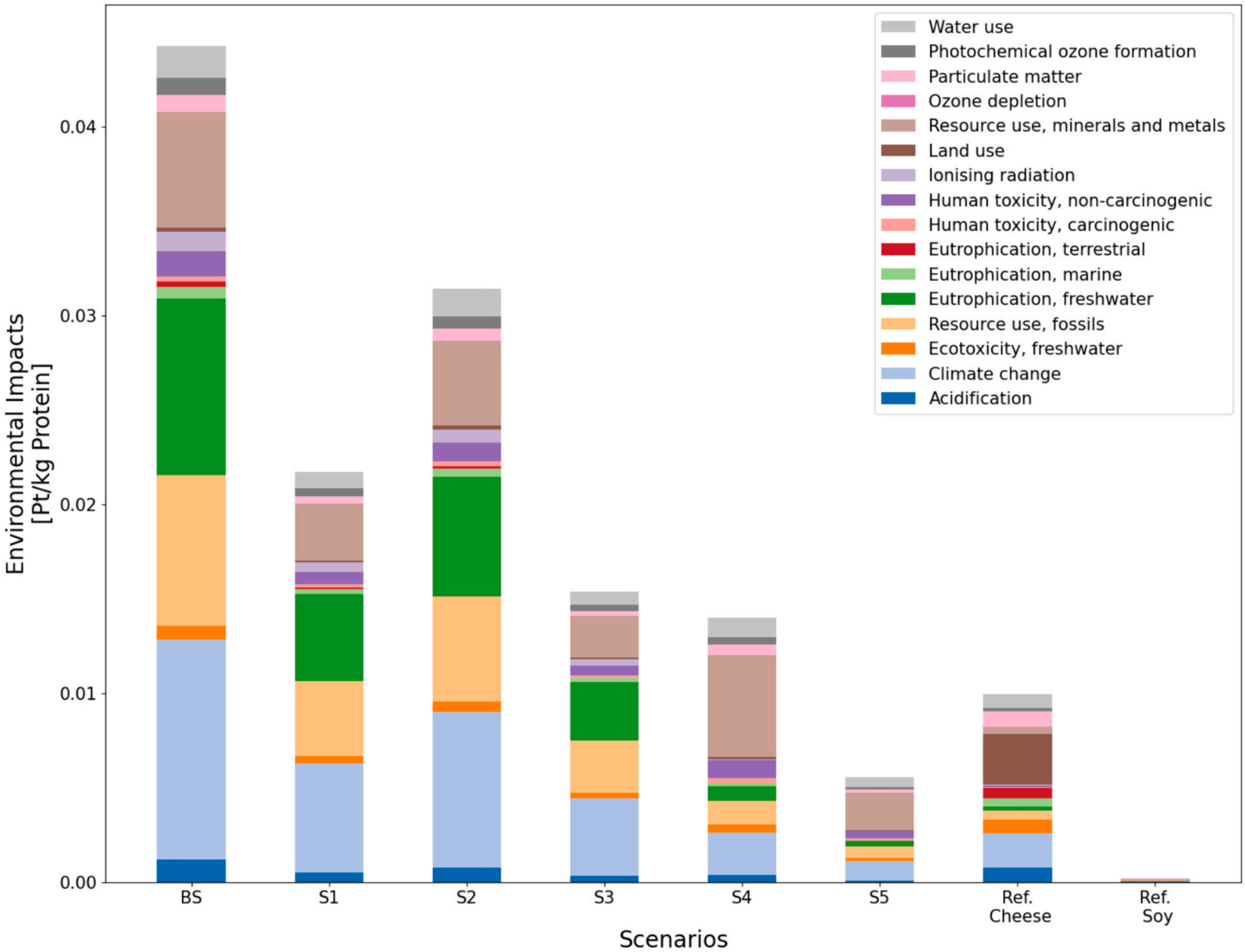

Fig. 6. Normalized and weighted results of producing 1 kg of wheatgrass protein concentrate powder, including contribution from all impact categories (all scenarios). BS: base case scenario; S1: Scenario 1 production efficiency; S2: Scenario 2 energy efficiency; S3: Scenario 3 efficiency improvement; S4: Scenario 4 energy source; S5: Scenario 5 best case; Ref.: reference.

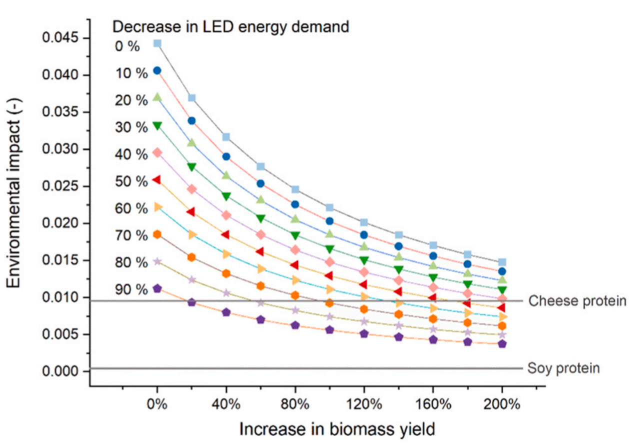

Fig. 7. Sensitivity of the environmental impact results on the LED energy efficiency and yield of producing 1 kg of wheatgrass protein concentrate powder.

of the biomass (67 kg) is still needed to produce 1 kg of protein. It could be concluded that yield and energy efficiency are the key points of environmental performance of a vertical farming system producing wheatgrass. In other words, under current electricity mix in Germany, more than 90 % of the energy must be saved or the yield of the wheatgrass must be tripled, so that the wheatgrass protein can be

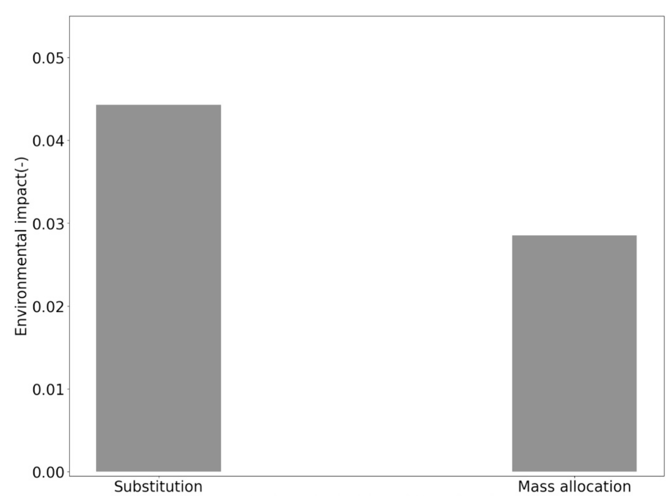

Fig. 8. Sensitivity of the environmental impact results on the choice of methods to deal with multifunctionality of producing 1 kg of wheatgrass protein concentrate powder.

competitive. Consistent with prior research, the results of this study prove as well, that the potential of vertical farms is viable primarily at locations with a high share of renewable energy in the grid. On the condition that production is optimized, and 100 % renewable energy sources are used, the environmental impact can be reduced to just 54.7 % of the cheese protein. These results indicate the potential of wheatgrass produced from vertical farms to serve as a substitute for animal-based protein such as cheese. Nonetheless, due to the substantial energy demands associated with vertical farming, this approach should not aim to replace plant-based protein sources, which generally have a lower environmental impact.

In the present configuration of the vertical farming system, most of impact categories are not favourable when compared against wheatgrass grown with other agricultural practices such as open-field or greenhouse. However, less land use stands out as one of the key advantages. The up-scaled OrbiPlant® system can achieve a tenfold increase in cultivation area within the same spatial footprint compared to traditional open-field or greenhouse methods. Compared to conventional vertical farms, the OrbiPlant® can be integrated into a greenhouse so that natural sunlight can be partially used for the plants, which reduces energy consumption. Further research should be carried out to investigate the possible improvement in yields and to see what level of environmental benefits can be achieved. Another perspective of the research could be the inclusion of other benefits into the sustainability assessment, especially the improvement in local food security. One possibility is to integrate the LCA with social life cycle assessment (S-LCA), so that the boundary of sustainability could be extended to social aspect as well. Talking about wheatgrass, further research should also consider other health benefits of wheatgrass, which have not been considered by the FU yet. The consideration of the other nutritional values besides protein content would be important to allow a more comprehensive comparison. In addition, alternative forms of consumption such as wheatgrass juice offer another possibility of utilizing wheatgrass, which reduces the loss at protein extraction and thus increases the utilization rate of the wheatgrass biomass. A comparative LCA between different wheatgrass products would be helpful to suggest what is the more sustainable way to consume wheatgrass.

Funding sources

The work presented in this paper stems from the research conducted for the Fraunhofer Flagship Project "FutureProteins", funded by the Fraunhofer-Gesellschaft.

CRediT authorship contribution statement

Zhengxuan Wu: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Maga:** Writing – review & editing, Validation, Project administration, Conceptualization. **Venkat Aryan:** Writing – review & editing, Validation, Conceptualization. **Andreas Reimann:** Writing – review & editing, Data curation. **Tobias Safarpour:** Data curation. **Stefan Schillberg:** Project administration, Funding acquisition.

Declaration of competing interest

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

Acknowledgements

The life cycle assessment presented in this paper stems from the research conducted for the project "FutureProteins" The authors would like to thank Josef Robert from Fraunhofer UMSICHT for providing primary data for the downstream processing of the biomass.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.08.031.

References

Al-Chalabi, M., 2015. Vertical farming: skyscraper sustainability? Sustain. Cities Soc. 18, 74–77.
Baldock, K., 2019. Vertical farming reaches New Heights in Germany with Fraunhofer IME.: the Association for Vertical Farming. https://vertical-farming.net/blog/2019/10/22/vertical-farming-fraunhofer-ime/. (Accessed 22 January 2024).
Barge, U., 2020. Analyzing the Environmental Sustainability of an Urban Vertical Hydroponic System (97 pp.).
Benke, K., Tomkins, B., 2017. Future food-production systems: vertical farming and controlled-environment agriculture. Sustainability: Science. Practice and Policy 13, 13–26.
Berardy, A., Johnston, C.S., Plukis, A., Vizcaino, M., Wharton, C., 2019. Integrating protein quality and quantity with environmental impacts in life cycle assessment. Sustainability 11, 2747.
Blom, T., Jenkins, A., Pulselli, R.M., van den Dobbelsteen, A., 2022. The embodied carbon emissions of lettuce production in vertical farming, greenhouse horticulture, and open-field farming in the Netherlands. J. Clean. Prod. 377, 134443.
Casey, L., Freeman, B., Francis, K., Brychkova, G., McKeown, P., Spillane, C., Bezrukov, A., Zaworotko, M., Styles, D., 2022. Comparative environmental footprints of lettuce supplied by hydroponic controlled-environment agriculture and field-based supply chains. J. Clean. Prod. 369, 133214.
Chakraborty, R., Kashyap, P., Gadhave, R.K., Jindal, N., Kumar, S., Guiné, R.P.F., Mehra, R., Kumar, H., 2023. Fluidized bed drying of wheatgrass: effect of temperature on drying kinetics, proximate composition, functional properties, and antioxidant activity. Foods 12.
Chalil, M., Meitha, K., Putra, R.E., Rahmah, F.A., Sinatra, R.R., Winanta, A.A.P., 2022. Wheatgrass microgreen with high antioxidants content in an urban indoor farming system. J. Biol. Sci. Technol. Man. 4, 26–34.
Ciroth, A., 2021. Life Cycle Inventory Analysis: Methods and Data. Springer International Publishing AG, Cham, p. 1216.
Clark, M.A., Springmann, M., Hill, J., Tilman, D., 2019. Multiple health and environmental impacts of foods. Proc. Natl. Acad. Sci. U. S. A. 116, 23357–23362.
Clune, S., Crossin, E., Verghese, K., 2017. Systematic review of greenhouse gas emissions for different fresh food categories. J. Clean. Prod. 140, 766–783.
Colomb, V., Ait Amar, S., Mens, C.B., Gac, A., Gaillard, G., Koch, P., Mousset, J., Salou, T., Tailleur, A., van der Werf, H.M., 2015. AGRIBALYSE ®, the French LCI Database for agricultural products: high quality data for producers and environmental labelling. OCL 22, D104.
Cores Rodríguez, F., Gallagher, E., Rai, D.K., Burgess, C.M., 2022. Nutritional and physiochemical properties of wheatgrass juice and preservation strategies. Food Chemistry Advances 1, 100136.
Devi, C.B., Bains, K., Kaur, H., 2019. Effect of drying procedures on nutritional composition, bioactive compounds and antioxidant activity of wheatgrass (Triticum aestivum L). J. Food Sci. Technol. 56, 491–496.
DIN, 2021a. Umweltmanagement - Ökobilanz - Anforderungen und Anleitungen (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020); Deutsche Fassung EN ISO 14044:2006 + Amd 1:2017 + Amd 2:2020. Beuth Verlag GmbH, Berlin 13 (020), 10.
DIN, 2021b. Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedinungen (ISO 14040:2006 + Amd 1:2020); Deutsche Fassung EN ISO 14040:2006 + A1:2020. Beuth Verlag GmbH, Berlin 13 (020), 10.
Eissa, H.A., Mohamed, S.S., Hussein, A.M.S., 2020. Nutritional value and impact of wheatgrass juice (Green Blood Therapy) on increasing fertility in male albino rats. Bull. Natl. Res. Cent. 44.
European Commission, 2013. Commission recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (1). Off. J. Eur. Union 56.
European Commission, 2020a. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions: Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people, Brussels, 26 pp. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562. Accessed 19 January 2024.
European Commission, 2020b. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system, Brussels, 20 pp. Accessed 14 January 2024.
European Commission, 2023. Agriculture and the Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/agriculture-and-green-deal_en. Accessed 14 December 2023.
FAO, 2004. Livestock's long shadow: environmental issues and options. Delhi xx, 340.
FAO, 2023. FAOSTAT: Food Balance. https://www.fao.org/faostat/en/#data. Accessed 09.023.
Farhangi, H., Mozafari, V., Roosta, H.R., Shirani, H., Farhangi, M., 2023. [Copy] optimizing growth conditions in vertical farming: enhancing lettuce and basil cultivation through the application of the Taguchi method. Sci. Rep. 13, 6717.
Finnveden, Göran, Hauschild, Michael Z., Ekvall, Tomas, Guinée, Jeroen, Heijungs, Reinout, Hellweg, Stefanie, Koehler, Annette, Pennington, David,

Suh, Sangwon, 2009. Recent developments in life cycle assessment. J. Environ. Manage. 91, 1–21.
FSVO, 2023. Swiss food composition database: soft cheese (average without fat reduced products). Federal Food Safety and veterinary. Office. https://naehrwertdaten.ch/en/search/#/food/340605 (Accessed 24 February 2024).
Gaillac, R., Marbach, S., 2021. The carbon footprint of meat and dairy proteins: a practical perspective to guide low carbon footprint dietary choices. J. Clean. Prod. 321, 128766.
Gomiero, T., 2016. Soil degradation, land scarcity and food security: reviewing a complex challenge. Sustainability 8, 281.
Henchion, M., Hayes, M., Mullen, A.M., Fenelon, M., Tiwari, B., 2017. Future protein supply and demand: strategies and factors influencing a sustainable equilibrium. Foods 6.
Hertzler, S.R., Lieblein-Boff, J.C., Weiler, M., Allgeier, C., 2020. Plant proteins: assessing their nutritional quality and effects on health and physical function. Nutrients 12.
Hristov, A.N., Hanigan, M., Cole, A., Todd, R., McAllister, T.A., Ndegwa, P.M., Rotz, A., 2011. Review: Ammonia emissions from dairy farms and beef feedlots. Can. J. Anim. Sci. 91, 1–35.
Huebbers, J.W., Buyel, J.F., 2021. On the verge of the market - plant factories for the automated and standardized production of biopharmaceuticals. Biotechnol. Adv. 46, 107681.
Huft, A., Engel, P., van Gemmern, A., Rueller, L., Robert, J., 2023. Optimizing protein recovery from plant substrate using ultrafiltration: a case study on wheatgrass. Journal of Agriculture and Food Research 13, 100653.
Islam, M.Z., Park, B.-J., Lee, Y.-T., 2021. Influence of temperature conditions during growth on bioactive compounds and antioxidant potential of wheat and barley grasses. Foods 10.
Kalantari, F., Tahir, O.M., Joni, R.A., Fatemi, E., 2018. Opportunities and challenges in sustainability of vertical farming: a review. J. Landsc. Ecol. 11, 35–60.
Kaup, C., Wollscheid, B., Swiderek, M., 2019. Freie Kühlung von Rechenzentren: Welche Lösung ist die richtige? 11, 36–40.
Kaur, N., Singh, B., Kaur, A., Yadav, M.P., Singh, N., Ahlawat, A.K., Singh, A.M., 2021. Effect of growing conditions on proximate, mineral, amino acid, phenolic composition and antioxidant properties of wheatgrass from different wheat (Triticum aestivum L.) varieties. Food Chem. 341, 128201.
Lang, C., Daniel, H., Birner, R., Reich, M., 2017. Bioökonomie für eine nachhaltige Proteinversorgung – Zur Bedeutung tierischer Produkte und biobasierter Innovationen, 41 pp. https://www.biooekonomierat.de/media/pdf/archiv/hintergrundpapier-proteinproblematik.pdf. Accessed 16 July 2024.
Li, T., Roskilly, A.P., Wang, Y., 2018. Life cycle sustainability assessment of grid-connected photovoltaic power generation: a case study of Northeast England. Appl. Energy 227, 465–479.
Lubna, F.A., Lewus, D.C., Shelford, T.J., Both, A.-J., 2022. What you may not realize about vertical farming. Horticulturae 8.
Martin, M., 2023. Life cycle management in vertical farming: insights from vertical farming sustainability assessments. Acta Hortic. 235–242.
Martin, M., Elnour, M., Siñol, A.C., 2023. [Duplikat] environmental life cycle assessment of a large-scale commercial vertical farm. Sustain. Prod. Consum. 40, 182–193.
Michaelsen, K.F., Greer, F.R., 2014. Protein needs early in life and long-term health. Am. J. Clin. Nutr. 99, 718S–722S.
Morgan Pattison, P., Hansen, M., Tsao, J.Y., 2018. LED lighting efficacy: status and directions. C. R. Phys. 19, 134–145.
Oh, S., Lu, C., 2022. Vertical farming - smart urban agriculture for enhancing resilience and sustainability in food secur. J. Hortic Sci. Biotech. 98, 133–140.
Patil, N.L., Kulkarni, A.A., Amalnerkar, D., Kamble, S.C., 2022. Exploration of wheatgrass as functional food by using urban agriculture models for regulating growth & nutrients. S. Afr. J. Bot. 151, 284–289.
Pedersen, A.N., Cederholm, T., 2014. Health effects of protein intake in healthy elderly populations: a systematic literature review. Food Nutr. Res. 58.
Pinstrup-Andersen, P., 2018. Is it time to take vertical indoor farming seriously? Glob. Food Sec. 17, 233–235.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360, 987–992.
Qin, P., Wang, T., Luo, Y., 2022. A review on plant-based proteins from soybean: health benefits and soy product development. J. Agric. Food Res. 7, 100265.
Rabbi, B., Chen, Z.-H., Sethuvenkatraman, S., 2019. Protected cropping in warm climates: a review of humidity control and cooling methods. Energies 12, 2737.
Rizzo, G., Baroni, L., 2018. Soy, soy foods and their role in vegetarian diets. Nutrients 10.
Röös, E., Carlsson, G., Ferawati, F., Hefni, M., Stephan, A., Tidåker, P., Witthöft, C., 2020. Less meat, more legumes: prospects and challenges in the transition toward sustainable diets in Sweden. Renew. Agric. Food Syst. 35, 192–205.
Saerens, W., Smetana, S., Campenhout, L., Lammers, V., Heinz, V., 2021. Life cycle assessment of burger patties produced with extruded meat substitutes. J. Clean. Prod. 306, 127177.
Sala, S., Cerutti, A.K., Pant, R., 2018. Development of a Weighting Approach for the Environmental Footprint. Publications Office of the European Union, Luxembourg, p. 146.
Schmidt Rivera, X., Rodgers, B., Odanye, T., Jalil-Vega, F., Farmer, J., 2023. [Duplikat] the role of aeroponic container farms in sustainable food systems - the environmental credentials. Sci. Total Environ. 860, 160420.
Sonesson, U., Davis, J., Flysjö, A., Gustavsson, J., Witthöft, C., 2017. Protein quality as functional unit – a methodological framework for inclusion in life cycle assessment of food. J. Clean. Prod. 140, 470–478.
STATISTA, 2023. Projected vertical farming market worldwide from 2022 to 2032. https://www.statista.com/statistics/487666/projection-vertical-farming-market-worldwide/. Accessed 26 July 2023.
Stiles, W., Wootton-Beard, P., 2017. Vertical farming: a new future for food production? https://businesswales.gov.wales/farmingconnect/sites/farmingconnect/files/technical-article-vertical-farming-final.pdf.
Tuomisto, H.L., 2019. Vertical farming and cultured meat: immature technologies for urgent problems. One Earth 1, 275–277.
U.S. Department of Agriculture, 2019. Agricultural Research Service. FoodData Central. fdc.nal.usda.gov.
United Nations, 2019. World Population Prospects 2019: Highlights. Statistical Papers - United Nations (Ser. A), Population and Vital Statistics Report. United Nations, Department of Economic and Social Affairs; Population Division, New York (143 pp.).
van Delden, S.H., SharathKumar, M., Butturini, M., Graamans, L.J.A., Heuvelink, E., Kacira, M., Kaiser, E., Klamer, R.S., Klerkx, L., Kootstra, G., Loeber, A., Schouten, R. E., Stanghellini, C., van Ieperen, W., Verdonk, J.C., Vialet-Chabrand, S., Woltering, E.J., van de Zedde, R., Zhang, Y., Marcelis, L.F.M., 2021. Current status and future challenges in implementing and upscaling vertical farming systems. Nat. Food 2, 944–956.
van Gerrewey, T., Boon, N., Geelen, D., 2022. Vertical farming: the only way is up? Agronomy 12, 2.
van Rysselberge, P., Röös, E., 2021. Carbon Footprint of Meat, Egg, Cheese and Plant-Based Protein Sources: Compilation of Data and Discussion of Assessing the Climate Impact in the WWF Swedish Meat Guide. Swedish University of Agricultural Sciences, Uppsala, p. 41.
Vogel, S., Schillberg, S., 2017. Device for promoting the growth of plants. https://worldwide.espacenet.com/patent/search/family/058800740/publication/WO2018220011A1?q=WO2018220011.
Vogel, S., Schillberg, S., 2023. Device for automated plant cultivation. https://worldwide.espacenet.com/publicationDetails/biblio?CC=DE&NR=112022000709T5&KC=T5&FT=D&ND=&date=20231102&DB=EPODOC&locale= (Accessed May.03.2024).
Wang, H.H., 2022. The perspective of meat and meat-alternative consumption in China. Meat Sci. 194, 108982.
Weidner, T., Yang, A., Forster, F., Hamm, M.W., 2022. Regional conditions shape the food-energy-land nexus of low-carbon indoor farming. Nat. Food 3, 206–216.
Wildeman, R., 2020. Vertical Farming: A Future Perspective Or a Mere Conceptual Idea?: A Comprehensive Life Cycle Analysis on the Environmental Impact of a Vertical Farm Compared to Rural Agriculture in the US (Master Thesis, Zwolle, 116 pp.).
Yu, H., Yu, H., Zhang, B., Chen, M., Liu, Y., Sui, Y., 2023. Quantitative perturbation analysis of plant factory LED heat dissipation on crop microclimate. Horticulturae 9, 660.
Zampori, L., Pant, R., 2019. Suggestions for Updating the Product Environmental Footprint (PEF) Method. Joint Research Centre, Luxembourg, p. 248.