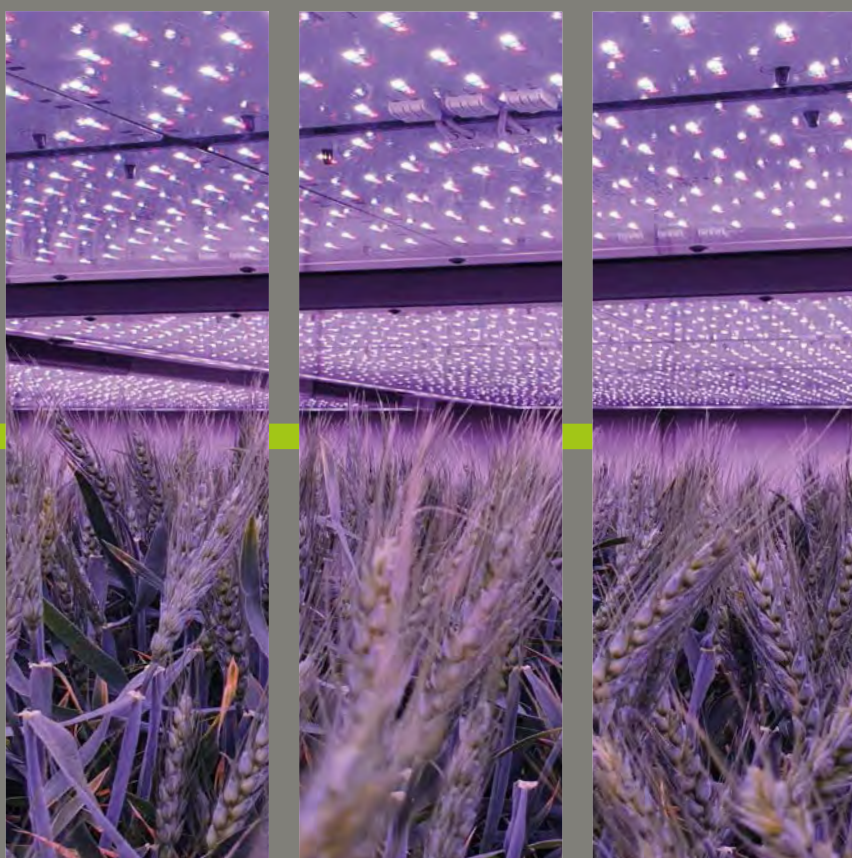




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Expert Forum on Controlled Environment Agriculture

Agriculture in controlled-environment production systems – Food security and export opportunities

A research strategy of the German Agricultural Research Alliance

Imprint

Expert Forum on Controlled Environment Agriculture

**Agriculture in controlled-environment
production systems Food security
and export opportunities**

Research Strategy of the
German Agricultural Research Alliance

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Agriculture in controlled-environment production systems – Food security and export opportunities

Research Strategy of the German Agricultural Research Alliance

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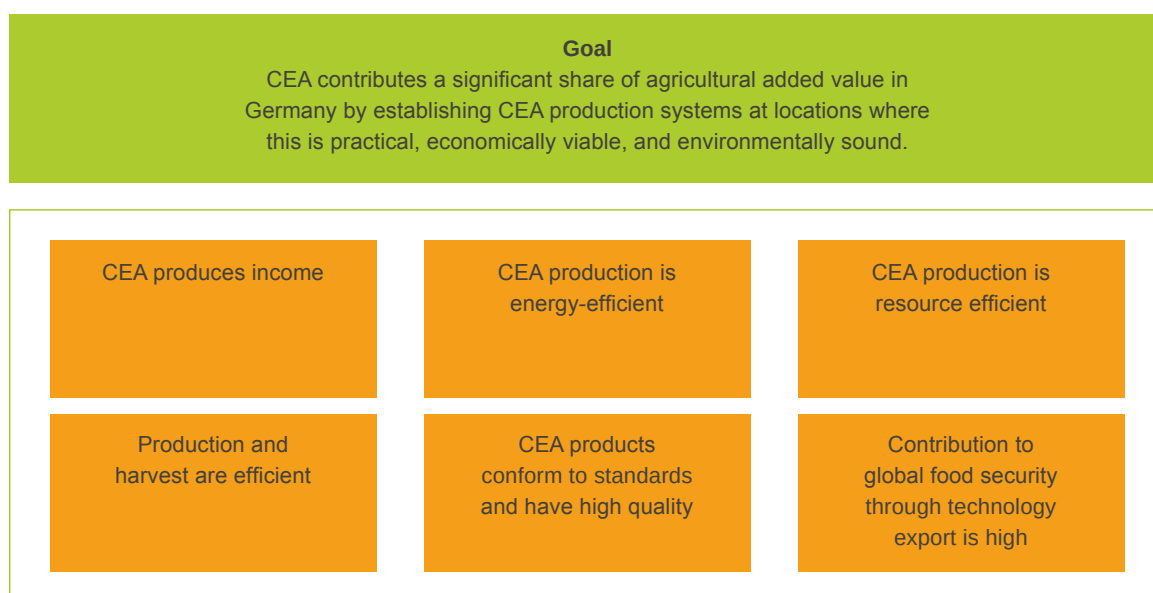
Key points at a glance

DAFA's Research Strategies

A DAFA research strategy aims to bring about a fundamental improvement in the strategic focus area. In order to address the core challenges facing the agricultural sector, agricultural research – which has traditionally been oriented towards the natural sciences and technology – must form alliances with other research disciplines (e.g., economics, environmental law). The strategy is intended to provide guidance to policy-makers at federal and state level regarding the core challenges. It is not intended to produce a comprehensive scientific review or to list all possible research topics relating to the strategic theme; in this respect, the strategy is not to restrict future calls for proposals from research funding bodies.

For a strategy to be successful, it is essential to (a) focus on an objective with a broad societal consensus and is formulated with sufficient clarity, and (b) derive a catalogue of measures that consistently directs scarce resources towards this core objective. The text of this research strategy is structured accordingly.

The content was drawn up by a panel of experts from among the member institutions of the DAFA. Drafts of the strategy were presented and discussed publicly. The strategy was endorsed as a DAFA strategy by the member institutions of the DAFA.



The following strategy sets out how food production in controlled environment agriculture (CEA) systems can make a key contribution to global food security within planetary boundaries. The strategy was developed by leading scientists and has been publicly discussed in detail.

Feeding a growing global population using existing agricultural production systems is reaching ecological limits, particularly in terms of climate, biodiversity, nutrient leaching and land use. CEA can significantly reduce this pressure by producing plants, fungi, insects, crustaceans (e.g., prawns) and fish within largely closed-loop systems.



Aeroponic cultivation of Moringa

■ CEA as an export commodity and a contribution to global sustainability goals

Germany boasts excellent research in the agricultural and natural sciences, engineering expertise, and outstanding know-how in control, automation and AI applications, which are already being utilised in experimental and commercial CEA facilities. These conditions make it possible to further develop CEA technology in a way that is internationally competitive, and to export it successfully.

For establishing a strong position in the global market, standardisation for worldwide use, regulatory frameworks and patents as well as coordinated further technology development and the establishment of a pilot market in Germany are crucial. Policy-makers and public authorities can provide significant support for this development through targeted funding for research, business and innovation.

CEA can thus make a decisive contribution to the implementation of several UN Sustainable Development Goals (SDGs) – including SDG 2 ‘Zero Hunger’, SDG 3 ‘Good Health and Well-being’, SDG 9 ‘Industry, Innovation and Infrastructure’ and SDG 12 ‘Responsible Consumption and Production’.

■ Current status of CEA technology and further development

CEA enables the production of consistently high-quality food close to the consumer and independent of location-specific factors such as climate, weather or soil quality. Furthermore, CEA, using stacked production areas for plants,

fungi, insects, crustaceans and fish massively increases land use efficiency. As a result, CEA enables significantly higher yields from the same area of land than 'traditional' field-based agriculture, which currently provides 60% of the global calories and protein for human consumption.

CEA's energy costs, which remain high at present, can be significantly reduced through targeted research and development, particularly through advances in production processes, lighting technology and the management of time-varying renewable energy use. In order to establish CEA as an effective complement to the agricultural sector, it is necessary to develop robust, automated and scalable systems that are both environmentally sound and economically viable.

■ Key challenges and strategic levers

CEA technology intended for export, must, above all, convince buyers by its quality and cost-effectiveness. As both climate change and technological developments – particularly in artificial intelligence – tend to progress exponentially rather than linearly, swift and coordinated action is essential.

This research strategy therefore focuses on the areas of production efficiency, system efficiency, product quality, safety and facilities engineering, as well as the necessary conditions (regulatory adjustments, societal acceptance, demand, training). The domestic and export markets are linked and should be considered together. Targeted collaboration on funding and policy-making between the relevant ministries is therefore advisable.

■ Most urgent measures for technological leadership and market opportunities

To achieve the objectives of quality leadership and marketability, this strategy recommends that the following measures be given priority in research funding and closely integrated within research projects:



- Increase **production efficiency** through optimised growing conditions, automated control systems and breeding adaptations.



- Improve **system efficiency** through the integrated production of several crop types, a circular economy and resource recovery.



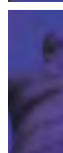
- Ensure **highest product quality and safety**.



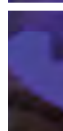
- Strengthen **the robustness, reliability and level of automation** of the facilities.



- Promote **standardisation, regulation and scalability**.



- Strengthen **social acceptance, market development and training structures**.



- Establish **pilot facilities on an industrial scale linked to research**.

1 Motivation



¹ Mombo, Vhiny-Guilley; Duvallet, Mathilde; Schaeffer, Michiel; Baarsch, Florent (2025): Have crops already reached peak suitability: assessing global climatic suitability decreases for crop cultivation. In: Environmental Research Letters 20 (3), p. 34009. DOI: 10.1088/1748-9326/adacfe.

² Hou, Deyi; Jia, Xiyue; Wang, Liuwei; McGrath, Steve P.; Zhu, Yong-Guan; Hu, Qing et al. (2025): Global soil pollution by toxic metals threatens agriculture and human health. In: Science (New York, N.Y.) 388 (6744), pp. 316–321. DOI: 10.1126/science.adr5214.

The world's population already stands at more than eight billion people and continues to grow. At the same time, climate change is already leading to a decline in arable land and crop yields¹, as well as increasingly frequent extreme weather events. There is an urgent need for action to secure the global food supply.

Further intensification of field-based agriculture (field farming, see glossary), without taking the sustainability of production into account, cannot meet these challenges. The use of mineral fertilisers, chemical plant protection and freshwater is already exceeding ecological limits in many places. This destabilises ecosystems, reduces their services and, in the long term, compromises the security of cultivation and harvests. Furthermore, the expansion of intensive farming methods in the field can accelerate the loss of biodiversity and lead to higher greenhouse gas emissions per hectare.

In addition, products from arable farming may also raise concerns due to local, site-specific factors: for example, because of the use of former industrial sites or because of soil contamination with heavy metals, environmental pollutants or microplastics. Globally, 14% of

land used for arable farming is contaminated with heavy metals such as arsenic or cadmium, which are absorbed by crops and enter the food chain².

The challenges facing arable farming are further exacerbated by economic and geopolitical upheavals, which can temporarily cut off entire regions from imports of essential food.

Against this backdrop, there is an urgent need for production systems that **are resilient to external economic shocks, environmentally sustainable and capable of operating year-round with relative independence from natural site-specific factors**. Controlled Environment Agriculture (CEA) offers a forward-looking solution here: it decouples food production from climate, weather, seasons and soil conditions, thereby enabling the production of food and animal feed of consistently high quality. Systems with resource cycles that are nearly closed-loop reduce environmental and health impacts. The area of open space that can be 'saved' by CEA, can be used for additional food production or to allow more biodiversity. CEA can reduce the dependence on imported food and animal feed.

Glossary

Agriculture	here: traditional agriculture, horticulture and aquaculture in the broadest sense, including CEA
Field farming	agriculture and horticulture practised outdoors
CEA	Controlled Environment Agriculture encompasses the production of plants – including algae –, fungi, insects, crustaceans and fish in a largely closed-loop system and under comprehensive control of environmental conditions (in particular light, temperature, water and nutrients)
CEA facility	a building equipped with technical installations in which production takes place
CEA system	a technical and biological production system, from rearing to harvest
CEA products	food and feed produced in a CEA system
Cultivated organism	cultivated species used in a CEA system

2 The potential of CEA



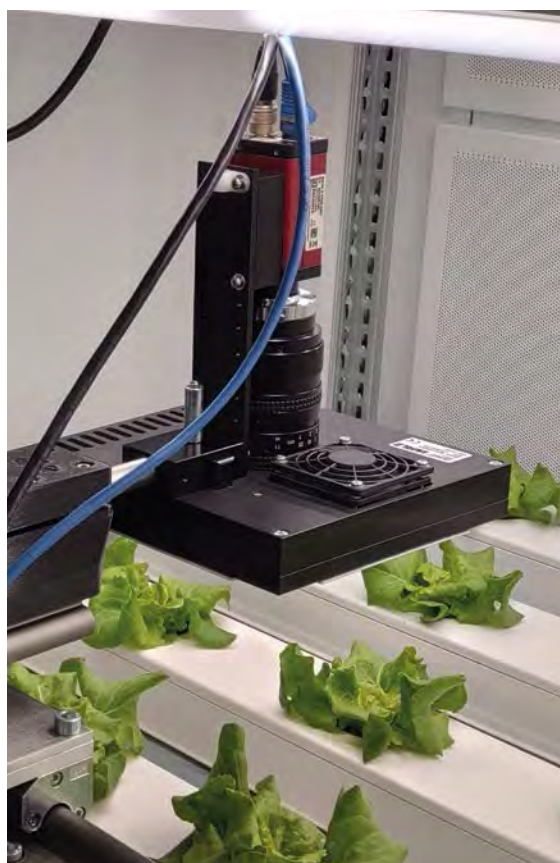
Agricultural production under controlled conditions – without the direct influence of seasons, climate and location – has the potential to become a cornerstone of a resilient, regional supply of food and animal feed. CEA enables the production of plants – including algae –, fungi, insects, crustaceans and fish in systems with nearly closed-loop resource cycles. Plants grow without substrate or in substrates under optimised conditions. Insect, crustacean and fish production primarily utilises species that, due to their requirements, are suited to being reared in controlled and confined environments. The energy required ideally comes from renewable sources. Systems that recycle nutri-

ents and water in a nearly closed loop significantly **reduce environmental impact**. Regionally distributed CEA facilities can reduce transport distances and, indirectly, the environmental impact as well. Waste materials from food production can be utilised by insects and fungi in CEA facilities.

Due to the closed environment, CEA requires **less use of plant protection products and antibiotics**, thereby reducing the effect on human health. Thanks to the controlled environment, CEA is particularly well-suited to products that must meet high standards of quality and consistency, such as high-quality food or medicinal plants, or that must have minimal contamination from the environment (e.g., microplastics, polychlorinated biphenyls 'PCBs', heavy metals).

The controlled environment enables significantly **higher productivity whilst maintaining consistently high product quality**. The potential for increasing production through the use of CEA is many times greater than, for example, through new varieties or cultivation methods in field agriculture (Table 1). Compared with traditional greenhouse solutions, CEA also offers advantages in terms of greater land efficiency when production space is limited. Furthermore, by linking single-trophic to multi-trophic systems, CEA enables the expansion of value chains and increases the sustainability of production. CEA is indispensable in extreme locations where people live for extended periods without the exchange of goods: research stations in Antarctica or extraterrestrial stations.

The advantages of CEA are particularly evident in regions where arable land is scarce, where



Measuring fluorescence to monitor plant conditions

Table 1. Global comparison of the theoretical potential of various single-species CEA systems with representative performance indicators (RPIs) for conventional field farming. Positive differences between CEA and conventional field farming are highlighted in green; negative differences in orange. The theoretical potential of CEA refers to units with 10 stacked production layers (vertical farming) on a basal area of 1 ha. For mushrooms, a bioreactor 10 m high and with a basal area of 1 ha was assumed. All figures for field farming are based on published data. Emissions and energy use relate to ongoing production in the field or in CEA facilities. The manufacture of machinery, farm buildings for housing equipment, the storage of materials or the construction of CEA facilities are not taken into account; these require detailed life-cycle assessments (see Section 8)³.

RPIs – based on 10 stacked production areas of 1 ha	Field crops, global	CEA with crops	CEA with algae	CEA with fungi	CEA with insects	CEA with fish
Average annual production [t ha ⁻¹]	4.5	1,900	1,900	23,040	32,140	12,410
Protein content [kg ha ⁻¹ year ⁻¹]	766	228,000	330,000	4,800,000	13,500,000	2,500,000
Land area [million ha]	697	2	2	0.1	0.1	0.3
Water use [l kg ⁻¹ food]	1,785	0.14	33	50	0.01	2,500
Energy consumption [kWh kg ⁻¹ food]	2.3	650	12	4	17	42
Greenhouse gas emissions [CO ₂ e kg ⁻¹ food]	3.3	~0	~0	~0	8	3
Plant protection products and antibiotics [kg ha ⁻¹ year ⁻¹]	1.6	~0	~0	~0	~0	~0
Nitrogen runoff and infiltration [kg ha ⁻¹]	5.4	~0	~0	~0	~0	not recorded
Phosphorus runoff and infiltration [kg ha ⁻¹]	0.1	~0	~0	~0	~0	not recorded

Change [%]	0 to 10	10 to 100	100 to 10,000	10,000 to 100,000
positive				
negative				

³ Calvo-Baltanás, Vanesa; Vilcinskis, Andreas; Brück, Thomas; Kloas, Werner; Wilke, Thomas; Rufino, Mariana; Henkel, Marius; Zorn, Holger; Monje, Oscar; Asseng, Senthil 2025, The future potential of controlled environment agriculture, PNAS NEXUS 4:4 pgaf078, adapted. DOI: 10.1093/pnasnexus/pgaf078



CEA facility with strawberries

climatic or site-specific conditions restrict field-based production systems, and where, at the same time, a high proportion of sustainably generated energy is available. The development of CEA technology is therefore highly relevant to achieving sustainability goals, both for densely populated countries in warmer regions and for industrialised nations in temperate latitudes⁴. CEA forms part of the Fraunhofer Society's 'Circular Bioeconomy for Germany' Roadmap.⁵

Viewed as a whole, CEA creates stable production opportunities within planetary boundaries⁴ – resilient and resource-efficient – and thus a type of future agriculture capable of successfully addressing social and environmental challenges. Due to its high land efficiency and potential for increased production (Table 1), CEA technology is also suitable as an exportable economic asset.

⁴ United Nations Development Programme (ed.) (2025): Controlled Environment Agriculture for Sustainable Development. Singapore. Available online at https://www.undp.org/sites/g/files/zskgke326/files/2025-01/controlled_environment_agriculture_for_sustainable_development.pdf

⁵ Buller, Jens; Daschner, Robert; Grimm, Lena; Hofer, Michael; Hüsing, Bärbel; Kraye, Julia et al. (2022): Circular Bioeconomy for Germany. A roadmap by the Fraunhofer-Gesellschaft for implementing the bioeconomy in Germany. Edited by the Fraunhofer Society, Berlin. Available online at <https://www.fraunhofer.de/content/dam/zw/de/forschung/FSF/bioeconomie/Roadmap-Circular-Bioeconomy-for-Germany.pdf>.

3 State of the art, globally



Simple CEA systems are already in productive use worldwide: on a small scale in Europe, and on a larger scale in the Middle East, Singapore, Indonesia, China and the USA. Applications for production facilities range from small boxes for domestic use, through cabinet-sized containers in supermarkets, to production facilities the size of a soccer field in desert regions. Aquatic production facilities for fish, crustaceans or algae are rarely stacked, but offer a compelling advantage in terms of production density compared with open-air facilities. In almost all facilities, production is limited to a single organism (single-species system); integrated systems (e.g., aquaponics combining fish and plants) are comparatively rare.

The technology used in CEA plant production generally originates from horticulture and is adapted accordingly to optimise lighting and to recycle water and nutrients. In land-based aquaculture and aquaponics systems with a controlled production environment, the water is ideally recirculated. CEA systems can be coupled with each other, either temporarily or permanently. System efficiency can be further increased when systems are coupled on demand. Germany and Europe possess relevant expertise in these core technologies and experience with industrially scaled systems.

Following initially promising economic prospects for CEA⁶ and the construction of even larger facilities in North America and East Asia during the 2010s, sharply rising energy costs combined with low energy efficiency, and high labour costs coupled with low levels of automation, have rendered many CEA ventures unprofitable. Nevertheless, economic consultants⁷ see great economic potential for CEA in the future due to (1) rising year-round demand for

fresh, sustainably and locally produced food, (2) the desire to reduce food waste, and (3) the opportunity to address labour shortages through automation. The key challenges currently facing the use of CEA facilities therefore lie in significantly reducing their energy consumption, standardising and automating processes and equipment, and scaling up promising pilot facilities to economically viable sizes.

The intended further development of the technology goes far beyond its use as a land-saving production alternative in Germany. In particular, it serves to develop an export technology and thus to strengthen Germany's position as an innovative exporting nation.



Strawberry nursery

⁶ Banerjee, Chirantan; Adenaeuer, Lucie (2014): Up, Up and Away! The Economics of Vertical Farming. In: *Journal of Agricultural Studies* 2 (1), pp. 40–60. DOI: 10.5296/jas.v2i1.4526.

⁷ Aulbur, Wilfried; Schell, Giovanni; Barbier, Eva (2023): *Controlled Environment Agriculture: Opportunities and challenges*. Edited by Roland Berger. Available online at "https://www.rolandberger.com/publications/publication_pdf/CEA-Roland-Berger-Publication.pdf" "https://www.rolandberger.com/publications/publication_pdf/CEA-Roland-Berger-Publication.pdf", last accessed on 16 March 2026.

4 Technology exports as a contribution to gross domestic product



Germany exports and imports goods depending on where they can be manufactured at higher quality or lower cost. As a country with few natural resources, Germany relies on the export of technological products to generate the financial resources needed to import other goods. Almost one in four jobs depends on exports, and 42% of Germany's gross domestic product (GDP) is derived from exports (2024). Exports thus make a significant contribution to tax revenue and overall economic prosperity.

Of particular strategic interest is the further development of a knowledge- and innovation-based economy that generates high added value and creates highly skilled jobs. High-tech products account for 14% of German exports (2022). Research, teaching and practical experience in the development of high-tech in-

dustries⁸ are closely intertwined and strengthen not only exports but also Germany's international standing and geopolitical influence, as highlighted in Germany's High-Tech Agenda⁹.

CEA can meet the growing global demand for high-quality, sustainably produced food (see Table 1). The targeted development of an export segment for CEA technology thus offers Germany the opportunity to tap into an additional, growing market and to further enhance its technological competitiveness. It is therefore in Germany's interest to promote the development of this technology, even though, by global standards, CEA in Germany is unlikely to achieve the same significance as in other countries and regions due to relatively fertile soils and continuing comparatively favourable climatic conditions.



CEA facility with sweet potatoes

⁸ High-technology products are defined as 'goods whose manufacture involves a high level of research and development' – Loschky, Alexander; Triebkorn, Elena (2011): Globalisierung des Fortschritts – Außenhandel mit Hochtechnologieprodukten und technologischen Dienstleistungen. In: Wirtschaft und Statistik Wiesbaden, pp. 920–931. Available online at <https://www.destatis.de/DE/Methoden/WISTA-Wirtschaft-und-Statistik/2011/09/globalisierung-92011.pdf>.

⁹ Federal Ministry of Research, Technology and Space (ed.) (2025): High-Tech Agenda Deutschland. Berlin. Available online at https://www.bmfr.bund.de/SharedDocs/Publikationen/DE/L/31881_Hightech_Agenda_Deutschland.pdf, last accessed on 16 March 2026. – p. 36: Funding for research, technology and innovation in the key market of the circular economy

5 Research addressing CEA



To ensure that companies can successfully implement CEA production, public research should support the further development of CEA technology: for example, in improving energy efficiency, optimising the use of production space, precisely controlling growing conditions, automating production steps, enhancing the robustness and efficiency of facilities and production processes, and implementing measures to protect the health of animals and plants. The resulting improvement in food production and its resilience, as well as the enhancement of the country's technological competitive advantage, is in both the public and economic interest. Funding programmes should be geared towards the targeted Technology Readiness Levels (TLR), ranging from basic research – for example, on the microbiome – through to the construction and operation of pilot facilities.

As demand for CEA is set to rise exponentially rather than linearly due to climate change, global population growth and the increasing threat to biodiversity, research funding must first address the most pressing challenges in the development of CEA. This research strategy provides recommendations to this end. It also takes into account that societal acceptance of CEA products is a key factor for success.

Germany, being a hub for research and development, is of fundamental importance for the continuous advancement of CEA technology, the development and maintenance of expertise, and the demonstration of its successful application. If scaling up and market penetration were to take place exclusively in the target countries, Germany would lose out on practical experience as well as opportunities for experimentation and training. The rationale behind the research strategy outlined here is therefore

based on the assumption that German policymakers will pursue two objectives: firstly, market leadership in CEA facilities for export; and secondly, the establishment of CEA in Germany as a pilot market and a location for development, as well as a building block for improving self-sufficiency.

The following sections describe how these two objectives can be achieved. A further section outlines supporting measures relating to sustainability, operational safety, food safety, training and the pursuit of strategic objectives. As the proposed measures are interlinked and have varying development timescales, an overview follows at the end, setting out the order in which they should be addressed in order to achieve the goal of CEA products making a decisive contribution to food security.



Wheat in hydroculture

6 Market leadership in CEA technology



CEA technology from Germany must prove its worth in the face of international competition in order to achieve market leadership. This is essentially achieved through higher production efficiency, greater cost-effectiveness, improved system efficiency, reduced environmental and health impacts, or higher product quality. The successful integration of CEA facilities into urban areas or into existing infrastructure also represents an important selling point.

6.1. Higher production efficiency

Production efficiency corresponds to the ratio between the yield achieved and the resources used. The need for more efficient food production is particularly acute in regions of the world facing water scarcity, frequent extreme weather events and, at the same time, a growing population. This need will continue rising due to climate change. Consequently, these regions also offer the greatest short-term potential for CEA technologies and products. However, particularly in hot, dry regions, sufficient climate-neutral energy could also be provided to operate the energy-intensive CEA facilities. Regions and locations where geothermal energy or industrial waste heat is available are also suitable sites for CEA.

In principle, greater production efficiency can be achieved through two means:

■ Optimising the ratio of resources to yield:

a) A lower demand for energy, water, nutrients and land area, whilst maintaining the same yields and quality, increases resource efficiency. b) Higher yields achieved through more favourable growing conditions, safeguarding the health of cultivated organisms, developing adapted varieties or breeds, and improved harvesting methods whilst main-

taining the same level of resource use increase production efficiency. c) Improved process control through sophisticated control strategies and early anomaly detection – for example, through the use of artificial intelligence – also increases yield and resource efficiency. d) Coupled systems increase the utilisation of internal resources and thus contribute to resource efficiency.

■ Reduction of resource losses and waste:

Closed-loop systems and the utilisation of by-product streams, for example through the recovery of operating materials from waste, increase overall efficiency.

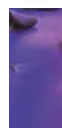
In order to fully exploit the potential of current CEA systems using a single product organism, these systems must be significantly enhanced through research and innovation. In our view, the priorities are as follows:



1. to develop sustainable and energy-efficient cultivation and husbandry methods that are particularly suitable for CEA,



2. to select more suitable species and varieties and develop more suitable breeds,



3. to reduce the costs of means of production, and



4. to develop methods that minimise losses due to pests and contamination.

6.2. Economic viability

The economic viability of CEA production depends primarily on energy costs, investment costs, achievable product prices, market acceptance and the available alternatives to CEA production (Table 2).

As costs and prices can vary considerably depending on location and country, CEA facilities must be adaptable on a seasonal or permanent basis – particularly with regard to the control of growing conditions and the automation of cultivation and harvesting. Therefore, when designing the funding criteria, it should be borne in mind that not all product categories are equally suitable from an economic perspective for different site conditions; rather, certain product categories offer greater economic advantages.

Further economic benefits may arise when CEA facilities can flexibly adapt their energy use to fluctuating energy prices. Research should therefore investigate, both theoretically and experimentally, how a time-varying energy supply can be adjusted by regulating other growth parameters, and at what point an economically significant reduction in production occurs.

6.3. Higher system efficiency, reduced environmental and health impacts

In our view, the four key building blocks for greater system efficiency are the improvement of cultivation methods, the integration of CEA systems, the improvement of control and automation technology, and the enhancement of the robustness and reliability of CEA facilities.

Tabelle 2. Economic viability of CEA products depending on the (climatic) environment and situation.

Environment, situation	Products well-suited to CEA
Arid climate (high water demand)	Vegetables (e.g., lettuce, tomatoes, cucumbers), cereals
Temperate climate (concurrent open-field cultivation possible)	Products with high quality standards: spices, herbs, medicinal plants, active ingredients (oils, proteins, antibodies)
Protein requirements (in all climate zones)	Fungi, insects, fish, legumes, crustaceans
Temperate or cold climate	Berries, vegetables, tropical fruits
General	Propagation of planting material and young plants, from herbs to woody plants
General	Root vegetables (e.g., potatoes, radishes, wasabi, cassava), medicinal roots
local markets	Sprouts ('microgreens')
limited agricultural land, desire for a high degree of self-sufficiency	Cereals

The integration of animal and plant production systems, together with the cascading use of residues, offers great potential to significantly increase production in relation to resource input.

Advanced, production-efficient CEA facilities therefore consist of several integrated systems, such as animal–plant–fungus. However, integrated CEA systems are also technically more complex, involve higher maintenance costs and usually require compromises. An important research priority must therefore be to keep the economic viability of these solutions in mind by involving economic sciences.

High overall productivity is achieved when the costs of protecting cultivated species are reduced – for example, through preventative measures such as **integrated pest management or ensuring animal health and welfare**. Any protection considerations must therefore be taken into account at the earliest stage when implementing measures to increase productivity through physiological, technical and breeding methods, crop management, pathogen control, improved infrastructure and regulation ('protection by design'), insofar as this is economically viable.

However, as preventative measures alone are unlikely to be sufficient, the first step is to analyse the risk posed by inadequate protection – that is, under what circumstances an unacceptable risk arises and how great the expected damage would be. For such cases, projects aimed at improving production efficiency should also develop methods for detecting deviations, as well as supplementary protective and countermeasures. Research must therefore be systematic in nature and should be allocated sufficiently long project durations to this end.

Extensive automation of seedling production and rearing, growth monitoring, harvesting and waste treatment (collectively referred to as process control) contributes to the economic efficiency of the system. **Robotics** combined with **artificial intelligence** can respond to growth deviations more quickly and precisely than humans. At the same time, robotics reduces space requirements, thereby increasing the space efficiency of a CEA facility.

Measurement and sensor systems monitor the condition of cultivated CEA organisms and optimise it using control **and regulation technology**. Measurement and control technology is therefore of particular importance. Even single-species systems require sophisticated control and regulation technology; in the case of coupled systems, complexity increases considerably due to the large number of control variables and potential feedback loops. As the integration of such single-species systems has so far been little developed, it requires optimisation at both the single and multiple-species system levels in order to establish CEA as a cost-effective complement to conventional agriculture. Model-based algorithms and artificial intelligence can further improve the control, monitoring and automation of CEA facilities, thereby reducing costs.

Robustness – understood here as tolerance to errors – as well as the efficiency, adaptability and reliability of the used infrastructure, including its measurement and control technology, are crucial quality characteristics, also for international exports. Research aimed at increasing the **robustness and reliability** of CEA systems, as well as their control and regulation, must consider individual sub-systems whilst also keeping the robustness and effi-

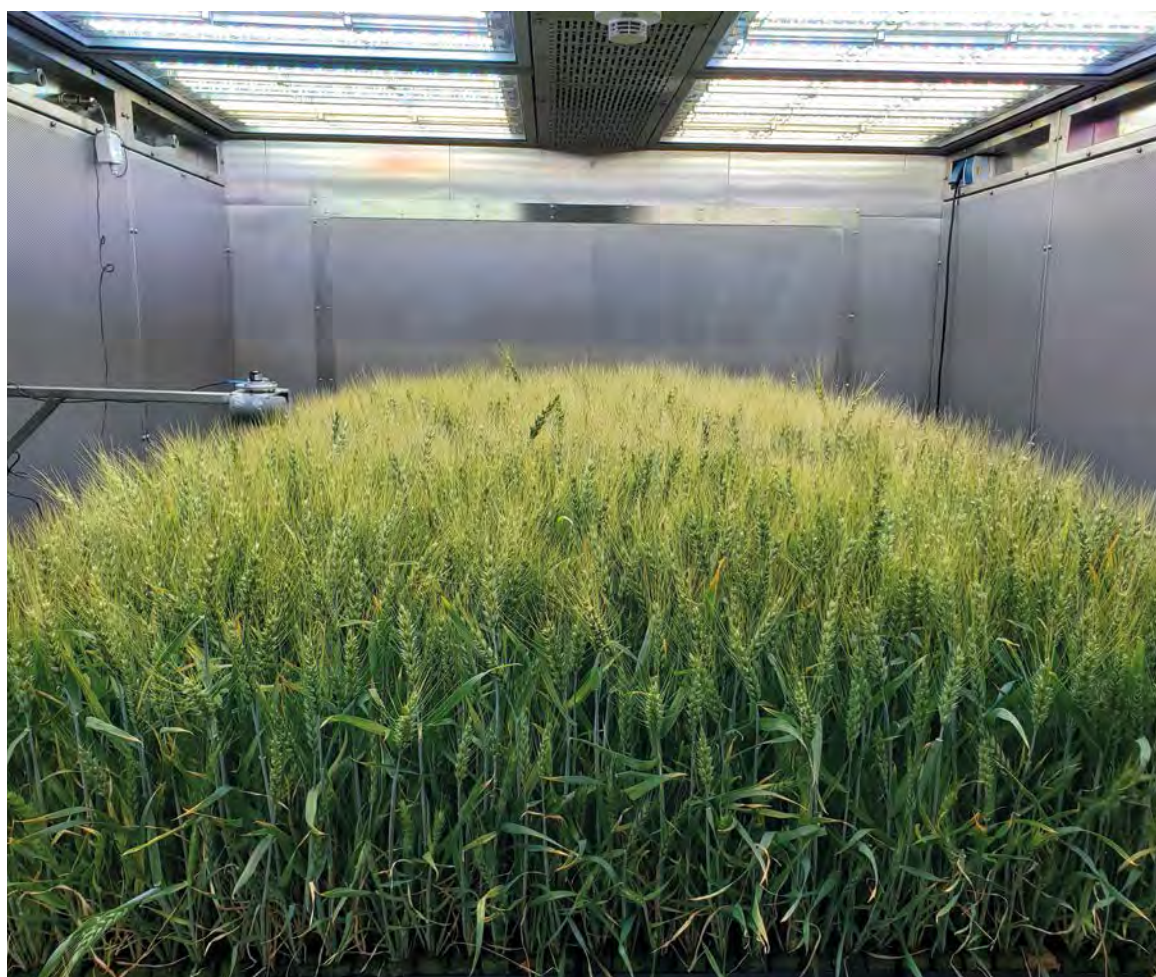
ciency of the overall system in mind. Of particular relevance here is the complex control of interconnected multi-system setups such as animal-plant-fungus. The extent of innovation funding should be guided by the expected contribution to value creation.

6.4. Higher product quality and consumer confidence

CEA facilities enable a consistently high quality of food and animal feed. This makes it easier to meet the quality standards for safe food intend-

ed for fresh consumption and for further processing. Controlled production in a closed environment also allows targeting specific **quality characteristics**, such as health-promoting compounds. However, there is still a considerable need for research to understand how environmental stimuli influence the formation of these compounds and how this can be controlled on a product-specific basis.

It is not only the composition of food that influences human health, but also the microorganisms present on and within it – the **microbiome**.



CEA facility with wheat



CEA facility with wooden barrels for prawn production

People who have been exposed to a diverse microbiome, particularly during childhood, are less susceptible to infections. Furthermore, there is evidence of a link between a restricted microbiome and the health of people in space stations. It is therefore essential to investigate the microbiome of CEA products, compare them with produce from uncontrolled or partially controlled environments, and assess any potential impacts on human health. Further research should also clarify how the microbiome can be specifically influenced under the controlled conditions of CEA facilities.

The **safety** of the feed and food produced is an indispensable quality characteristic. As CEA

facilities are not completely closed systems – resources and biological starting materials are introduced, and mature products are removed – this can lead to the introduction of microorganisms and substances that contaminate the end products. To prevent or limit such contamination, the same measures apply as those described above for the protection of crops. In addition, research should be conducted to determine whether human pathogens can also accumulate in CEA facilities over the long term and enter the food chain via the products.

Although CEA products can therefore meet **high quality and safety standards**, this novel production method may give rise to concerns

and scepticism among consumers. For a successful market launch, it is therefore important to assess the quality of CEA products and compare them with products from other production methods, in order to engage in a constructive dialogue with consumers. To this end, scientifically sound concepts and methods must be developed, which also include knowledge dissemination.

6.5. Establishment of CEA facilities: construction, modularisation, scaling

In principle, there are two construction approaches for **establishing new CEA facilities**: adapting existing buildings to the requirements of CEA facilities or constructing new buildings. In the interests of sustainability, new construction should only be considered if existing buildings (e.g., office buildings, residential buildings, factories, underground car parks, live-stock sheds) cannot be converted cost-effectively. New buildings should preferably be constructed using sustainably produced materials such as timber. Newly produced concrete or steel should only be used if robust life cycle assessments demonstrate clear advantages.

Both new and existing buildings must be designed with sustainability in mind so that material and energy flows can be closed. Research funding should therefore support sustainable structural systems through concept and innovation challenges and subsequent implementation projects. In addition, concept contests for the refurbishment of existing buildings appear to be a sensible approach.

The **standardisation** of processes, infrastructure and dimensions can create further eco-



Modular CEA growth cabinet

nomic benefits. It is therefore important to develop international norms and standards at an early stage, in close coordination between research and industry. Germany should take an active role in line with this strategy and initiate the relevant standardisation processes.

Standardised production modules could simplify construction and operation by utilising modules that are compatible worldwide and

adapting them to operational requirements. Such modularisation also reduces the effort involved in developing individual control and regulation systems for each plant, thereby strengthening the national and international competitiveness of CEA technologies.

A major challenge lies in scaling up small-scale experimental research facilities into large-scale production plants that can serve as models for exportable facilities. Determining how such **scaling** can best be achieved and under what conditions is a key innovation task that requires close collaboration between businesses and research institutions. In doing so, up-stream and downstream sectors along the value chain must also be taken into account – from breeding material and early life stages, through integration into existing supply infrastructure, to transport and utilisation.

6.6. Requirements for research and innovation

Funding for research and development in the field of CEA production must be designed for the long term whilst also being able to respond to specific research questions in the short term. To this end, it should pursue two parallel strands: firstly, the long-term research and development of coupled two- or three-species systems, which will most likely require several stages of iteration; and secondly, the targeted optimisation of existing single-species CEA set-ups within the framework of innovation projects. Applicants should set out the extent to which their research contribution will help to increase CEA production in Germany or globally.

Agritechnological research for CEA export markets should focus primarily on system opti-

misation by increasing yields (product efficiency) and, in particular, reducing energy and water consumption (resource efficiency). Facilities engineering and control and regulation technology must be particularly involved in this development to ensure that investment and operating costs remain aligned with the overall economic objectives.

In addition to the technological advancement of the systems, **agricultural economics and agricultural policy research** should analyse the economic potential of CEA exports and develop policy options that strengthen the international competitiveness of CEA systems manufactured in Germany.

The following must be considered in all **research and development projects**:

- The quality and safety of products produced in CEA must be equal to or higher than that of products from uncontrolled or partially controlled environments.
- Substances of concern in feed or food must not accumulate within the CEA system (for example, through leakage from the CEA infrastructure or migration within the CEA facility).
- The welfare of animals used in CEA facilities must be guaranteed. The development of housing environments, installations and regulations must take this into account.

The selection of breeding stock and the development of adapted breeds and varieties require extended development times and should therefore be funded early on and over a long term.

7 Germany as a pilot market



New production methods will only become established if they demonstrate their quality, suitability, performance and cost-effectiveness in practical use and are successful on the market. Simply funding research into CEA technology is not sufficient to achieve this.

Whilst policymakers could encourage companies to produce food using CEA through subsidies or economic incentives, a more economically efficient approach would be one in which CEA establishes itself largely by virtue of its own merits, with policymakers **primarily facilitating market access**. Agricultural research can develop suitable options for this. A preliminary study should analyse why CEA start-ups

have failed or succeeded in establishing themselves worldwide in recent years, in order to derive sound decision-making criteria for future funding priorities.

A key advantage of CEA is its independence from environmental factors. As a result, other location factors become more important, such as the availability of energy and water, proximity to sales markets and favourable conditions for facility construction. The policy-driven management of **regional development** requires scientifically sound proposals on how CEA can not only be established in urban areas but also usefully complement existing agricultural systems in rural regions. Furthermore, the societal



Vanilla production experimental facility

advantages and disadvantages of a centralised or decentralised distribution of CEA facilities should be assessed in order to guide policy decisions accordingly.

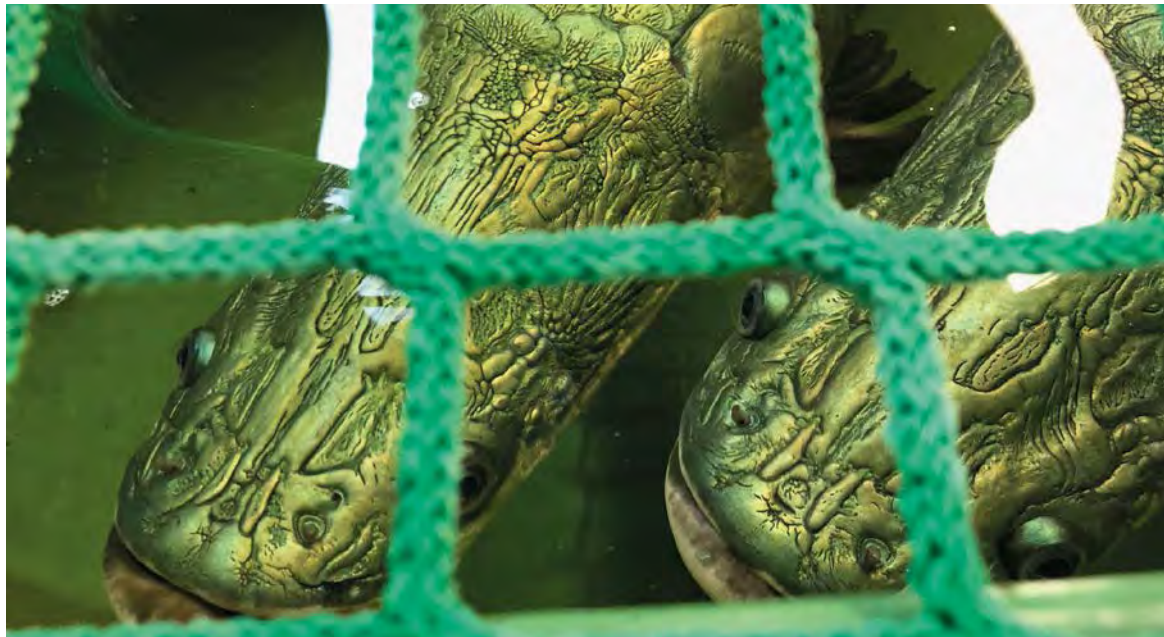
To ensure the resource efficiency and economic viability of CEA systems under German conditions, the bioeconomic context must be taken into account. By-products from agriculture and food processing can be used in CEA facilities for feed production, thereby reducing dependence on feed imports and minimising competition with food production.

A register of suitable and prioritised sites where CEA production is desired can serve as an important basis for business and regulatory decisions. To this end, scientifically sound and socially acceptable criteria must first be developed – for example, regarding energy and logistics infrastructure, soil, climate, nature and landscape conservation, as well as the revitalisa-

tion of rural areas. Furthermore, a favourable legal framework and streamlined approval procedures must be in place.

An industrial-scale CEA pilot facility makes it possible to investigate economies of scale experimentally, carry out targeted market research and establish CEA products on the German food market. To this end, sites need to be identified that are easily accessible, have the necessary infrastructure, offer access to affordable energy (and, in the case of CEA involving fish or crustaceans, access to affordable water), and where existing sealed surfaces can continue to be utilised. As these pilot facilities are intended to operate profitably whilst also providing scientific insights, public-private partnerships are particularly well-suited to their development.

At the same time, it is necessary to create a suitable **legal framework**: as several forms of



Arapaima gigas in Aquaculture



*Harvesting the larvae of the black soldier fly (*Hermetia illucens*)*

CEA production are not currently classified as agriculture under the law, all forms of CEA production must be placed on an equal legal footing with conventional agriculture. Correspondingly amended regulations should be prepared within the framework of research contracts and with the involvement of relevant industry associations. Furthermore, the legal conditions governing the use of residual materials for feeding insects for protein production should be adapted.

CEA products will only be **accepted** by end-consumers or the food processing industry if they are cheaper, of higher quality or otherwise more attractive than field-grown produce. Research should therefore specifically investigate:

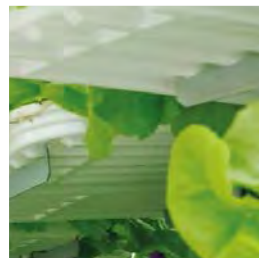
- which characteristics of CEA products, when compared with produce from existing pro-

duction systems – such as outdoor production, protected cultivation in greenhouses or open aquaculture – increase or decrease the acceptance of CEA products,

- which policy measures, funding initiatives and science communication strategies are suitable for addressing public concerns regarding CEA, thereby strengthening market integration; and
- how the economic sustainability and competitiveness of CEA products can be improved or secured in the long term in comparison with established agricultural production systems.

These studies should be carried out at regular intervals (e.g., every five years) in order to adapt policy and research funding accordingly.

8 Overall setting



Both the development of an export market and the establishment of a pilot market in Germany require reliable and objective means of comparison for different development and utilisation pathways for CEA. **Life Cycle Assessments** (LCAs), which take a systemic view of CEA – covering buildings, energy and water requirements, food production, circular economy and waste management, land use, soil sealing and climate impact – are well suited to this purpose. However, methods for conducting LCAs of this complexity have yet to be developed and established in accordance with ISO standards.

As crops and technical systems are constantly evolving, the methods and data foundations of LCAs must also be continuously updated. It therefore makes sense for research institutions and companies to provide the necessary data for the further development of LCAs in a standardised manner, and for a long-term research

programme to ensure the continuous development of LCAs.

CEA systems are subject to entirely different types of disruption than outdoor production. Research must therefore clarify how the **operational safety** of the facilities can be assessed, guaranteed, documented and, where necessary, restored in the event of accidental, unintentional or deliberate disruptions. It must be possible to derive changes to the technology used, the processes or the relevant legal standards from the results.

Similarly, ensuring food safety is an indispensable prerequisite for the use of CEA products. Accordingly, continuous testing is required to assess the food safety of CEA produce, and this must be organised in the most efficient manner possible in terms of manpower, costs and resources.



OrbiPlant facility at the Fraunhofer Institute for Molecular Biology and Applied Ecology



Aquaponics system for tomato and fish production

The complexity of CEA facilities and the demands placed on their robustness require specially trained staff in crop management, engineering, architecture and control systems. The requirements for expertise in integrated CEA systems are even higher. Accordingly, appropriate **training programmes** are required, which should be aimed at both domestic and international specialists in order to support the export of CEA facilities.

As research funding for the CEA is spread across several ministerial departments at federal and state level (departments for agriculture, food, the economy, energy, space, research and international cooperation), it is all the more important that the **results of this research are regularly collated and as-**

sessed by the relevant federal and state ministries, so that necessary further measures relating to research and economic policy can be derived and efficiently integrated into the research process (Figure 2).

The research community recognises the need for a centre of expertise and coordination that brings together results and data and supports professional exchange. Various models are possible for establishing such a centre – ranging from affiliation with a professional association to the creation of a ‘virtual hub’ (a platform for data exchange). These, however, are not part of this research strategy but should be discussed in dialogue between the federal government, the Länder, the research community and industry.

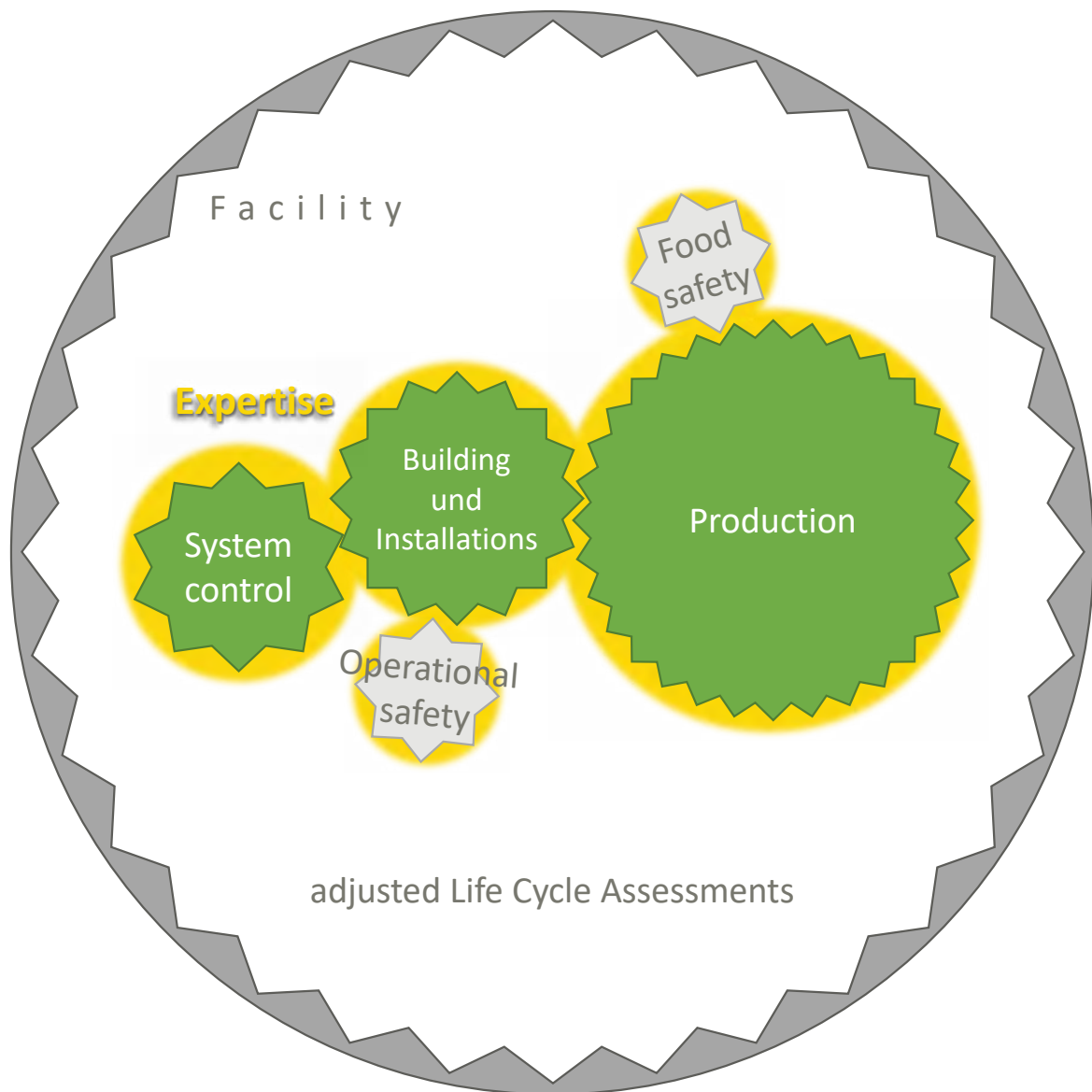


Figure 1. The tasks involved in food production in CEA facilities mesh together like cogs in a gear. Research into this area must be similarly interlinked.

9 Strategic prioritisation of measures



The varying development timeframes and their significance for the expansion of CEA require a clear prioritisation of research and development measures. We recommend the following prioritisation:

1. increase energy efficiency and reduce operating costs; select economically viable products and production processes, and adapt species and varieties through breeding;
2. align the legal framework in Germany and the EU for CEA production with the rules governing agricultural production,
3. assess consumer acceptance,
4. increase the level of automation,
5. establish a pilot facility containing research infrastructure,
6. develop LCA standards for comparisons and modelling,
7. link plant production with protein production from insects, fish, crustaceans and fungi,
8. make the production facilities' measurement and control technology more robust,
9. recycle waste materials and thereby prevent food waste,
10. ensure product quality and safety,

The research process should be coordinated in terms of timing to ensure close coordination between the individual research areas (Figure 2).

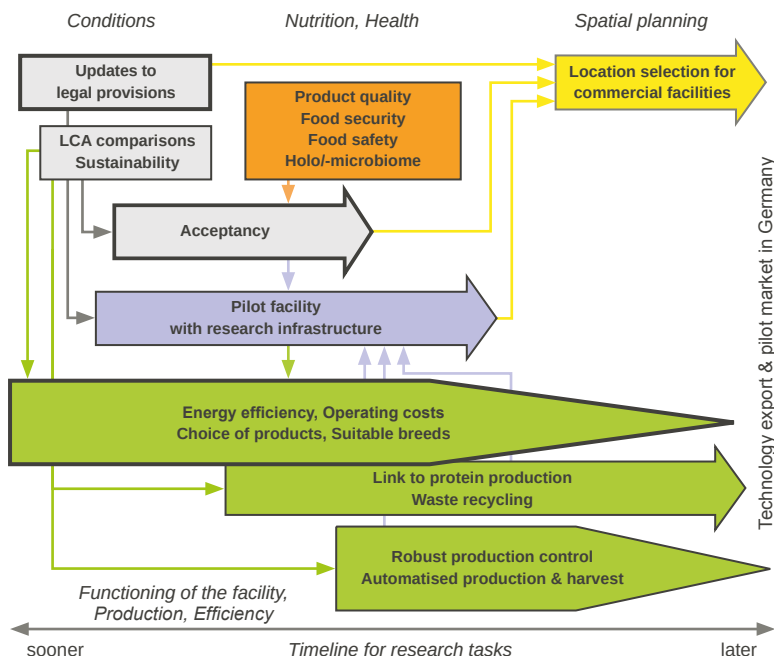


Figure 2. Idealised sequence of the key research tasks for CEA. Lines (lines with arrowheads) indicate necessary information flows. Boxes with triangular extension (►) indicate that the importance of the task diminishes over time. Boxes with arrowhead (➡) indicate that the task is ongoing or of a long-term nature.

10 Summary

From a German perspective, the greatest economic significance of CEA lies in the export of the technology, but also in the domestic production of high-quality food and animal feed. The basis for this is research, development and demonstration of the CEA technology in Germany. CEA complements conventional agriculture wherever arable land is scarce and sustainably sourced energy is available at low cost.

Given limited financial resources, research funding should focus on those tasks that contribute most significantly to the subsequent production of food and animal feed in CEA facilities. In our view, these include:

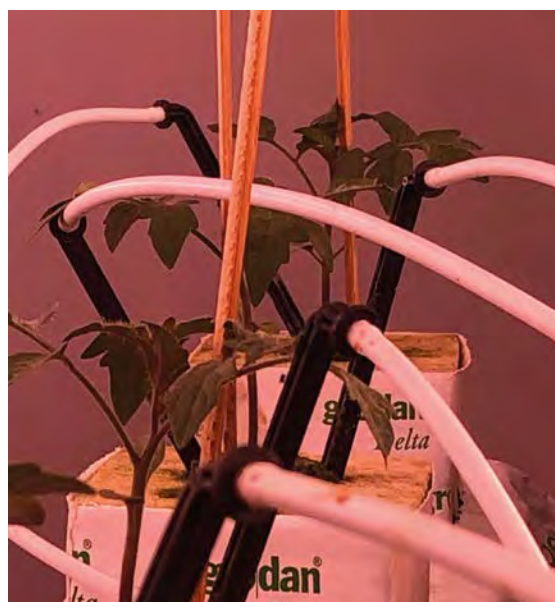
1. understanding the interactions between the production environment and the product and, building on this, developing control systems, measurement technology and monitoring systems for multi-component CEA facilities in order to increase both productivity (in particular energy efficiency) and product quality,
2. advancing building and energy technology to reduce costs,
3. closing material cycles as far as possible to conserve resources, and
4. ensuring the robustness and reliability of the production facilities and production processes, as well as the food safety of the products.

The promotion of research and innovation must be accompanied by policy measures that increase the acceptance of CEA products and systems in Germany as a pilot market. Social science research supports policymakers in identifying suitable approaches and addressing societal concerns in a targeted manner.

CEA builds on scientific excellence in agricultural research and decades of experience in engineering. It offers Germany the opportunity to develop a key technology that equally strengthens food security, resource efficiency and economic resilience.

In a world increasingly characterised by climate risks, geopolitical uncertainties and growing food demand, CEA is becoming a strategic tool for making food supply systems more independent, stable and sustainable.

Investment in CEA not only lays the foundations for Germany's own technological sovereignty, but also opens up a growing global market with significant potential for value creation, contributing to food systems security and resilience. Through a determined support of research and development of CEA systems, Germany can assume a leading position in this field – scientifically, economically and socially.



Irrigation of young tomato plants

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Thank you!

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Prof. Dr. Marc Boelhauve (South Westphalia University of Applied Sciences), Linda Homann (Federal Institute for Agriculture and Food), Dr. Andreas Müller-Belecke (Institute for Inland Fisheries e.V., Potsdam-Sacrow), Prof. Dr. Stephan Schneider (Nürtingen-Geislingen University of Applied Sciences for Economics and the Environment), Friedrich Loeffler Institute, Mecklenburg-Western Pomerania State Research Institute for Agriculture and Fisheries, and Max Rubner Institute.

We would also like to thank everyone who took part in the workshop in November 2025 for their contributions and the lively discussions.



CEA Workshop 2025, discussion of the draft strategy

Development of the strategy

In November 2021, the DAFA General Assembly resolved to establish a DAFA platform for the purpose of professional exchange and networking on 'Controlled Environment Agriculture'. The steering group for the platform was appointed, and its remit defined, in early 2022. At the first public meeting in Freising in autumn 2022, stakeholders from the field of CEA came together to present their research. At subsequent meetings of the steering group, discussions focused on how the research carried out by the individual institutes could be better coordinated and developed in the interests of society.

In March 2024, the members of DAFA endorsed the development of a research strategy on CEA. The steering group's draft strategy was presented to and discussed with an expert

audience at a workshop in November 2025. In addition to the scientific community, research funders, industry representatives, non-governmental organisations, practitioners and public authorities were also invited. The wealth of feedback provided the basis for further developing the strategy.

Following the presentation of the strategy and its formal adoption by the members of DAFA, the final strategy was published in autumn 2026 and serves as a guide for research funding.



CEA Strategic Workshop, autumn 2025, Thünen Institute, Braunschweig



Members of the DAFA



Universities



Freie Universität Berlin,
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Humboldt University of Berlin,
Albrecht Daniel Thaer Institute
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Friedrich-Wilhelms-Universität,
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Weihenstephan-Triesdorf University of Applied Sciences, agricultural faculties

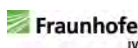
Other Research Institutes



The Association for Technology and Structures in Agriculture (KTBL)



Fraunhofer Institute for Interfacial Engineering and Biotechnology (FhG-IGB)



Fraunhofer Institute for Process Engineering and Packaging (FhG-IVV)



German Institute for Tropical and Subtropical Agriculture (DITSL)



Institute for Rural Development Research (IfLS)



Leibniz Institute for Agricultural Development in Transition Economies (IAMO)



Leibniz Institute for Agricultural Engineering and Bioeconomy (ATB)



Leibniz Institute for Horticultural Sciences (IGZ)



Leibniz Institute for Freshwater Ecology and Inland Fisheries within the Forschungsverbund Berlin (IGB)



Leibniz Centre for Agricultural Landscape Research (ZALF)



Leibniz Institute of Plant Genetics and Crop Plant Research



Potsdam Institute for Climate Impact Research (PIK)



Research Institute for Farm Animal Biology (FBN)



Research Institute of Organic Agriculture (FiBL), Germany



ZB Med – Information Centre for Life Sciences (ZB-Med)

Federal Research Institutes



Deutscher Wetterdienst (German Meteorological Service), Agrometeorological Research Centre (DWD-ZAMF)



Friedrich Loeffler Institute (FLI), Federal Research Institute for Animal Health



German Environment Agency (UBA)



German Federal Institute for Risk Assessment (BfR)



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Research Institutes of the States



Agricultural Centre for Cattle
Husbandry, Grassland Farming,
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Bavarian State Research Center
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Centre for Agricultural
Technology Augustenberg
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State Office for Consumer
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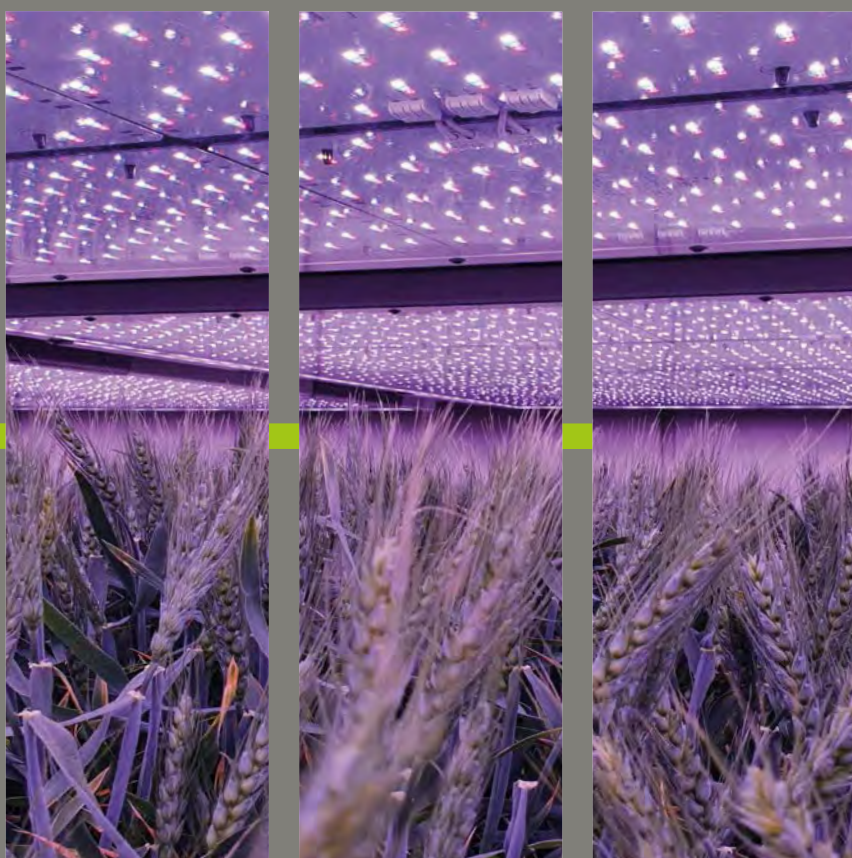
Teaching and Experimental
Station for Animal Husbandry –
Neumühle Farm (Hesse)



Technology and Support Centre
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