Leibniz-Institut für Agrartechnik und Bioökonomie

ATB Research Strategy

2024-2033

Content

Preamble

The ATB Research Strategy serves as a guiding framework for shaping and directing ATB's research efforts. It identifies ATB's strategic research priorities for the next 10 years, recognising the importance of adaptability and flexibility. Strategic implementation is paramount to the effective achievement of the research goals set.

The implementation process encourages continuous reflection and refinement of the research approach in response to newly developed scientific knowledge, policy agendas, emerging challenges and opportunities. This will also ensure that ATB remains agile in the setting and pursuit of its objectives and competitive in its research approach nationally and internationally.

Global challenges and need for innovations

Global challenges

It is widely recognised that humanity needs to move from fossil fuel dependency to a circular and sustainable bioeconomy. The bioeconomy paves the way for a more innovative, resource-efficient and competitive society that combines food security with the sustainable use of renewable resources for industrial purposes, while ensuring environmental protection (EU Bioeconomy Strategy[1]), strengthening competitiveness and creating jobs. Planetary boundaries, limited available resources and global challenges such as climate change, land and ecosystem degradation, biodiversity loss together with a growing population, require a paradigm shift from linear approaches to circular and highly efficient resource use[1].

Primary agricultural production is the backbone of providing food for the world's population and biomass for the production of bioenergy and bio-based products, and thus of sustainable and circular bioeconomy systems (SCBS) as a whole. The sustainability of agri-food systems, as targeted by the UN 2030 Agenda, is currently facing multiple challenges in interrelated areas: continued food and nutrition security, livelihoods and growth, biodiversity, climate vulnerability and sustainable use of natural resources, and resilience and use of natural resources[2,3,4,5,6,7]. The Food and Agriculture Organization (FAO) estimates that 800 million people are chronically hungry, 2 billion people are micronutrient deficient, over 650 million people will still be undernourished in 2030, and 6 million children die each year before the age of five[4,8]. The "triple burden of malnutrition" in the form of underweight, hidden hunger and overweight is a manifestation of undernutrition in the 21st century. At the same time, only about 25% of the total biomass produced each year is harvested, leaving large amounts of crop residues and agro-industrial by-products unused or underused. In addition, food losses and waste account for about 30% of agricultural production[4,9], which also poses an environmental threat, not to mention the economic and societal dimensions.

Current agricultural practices cause significant environmental damage and the resulting negative health impacts and health-related costs include: air pollution, particulate matter pollution, nitrates in groundwater, climate change, spread of antimicrobial resistance, loss of biodiversity, to name but a few[8] The resulting burdens are, at present, largely externalised to society.

At the same time, as a producer of biomass, agriculture is more affected by the consequences of the climate crisis than almost any other sector, and urgently needs solutions to survive under current and future environmental conditions. The idea that humans stand outside the natural world, shaping and transforming it, urgently needs to be replaced, leading to entirely new economic opportunities (Dasgupta, 2021[10]), and these new approaches also need to be implemented in agricultural production.

The United Nations' 17 Sustainable Development Goals (SDGs) provide a framework for solutions to the current challenges. Agriculture, including livestock production, will play a central role in achieving the SDGs[4,8.] The UN 2030 Agenda provides a framework to address the world's current challenges, with the agri-food sector central to achieving almost all 17 SDGs (UN, 2018[11]). At the European level, the importance of a transformation is reflected in two clusters 'Digital, Industry and Space' and 'Climate, Energy and Mobility' which are prioritised in Horizon Europe looking into the R&I future priorities for 2025-2027[12]. One of the research topics identified as a priority is the transformation of forest, agricultural and food systems towards long-term sustainability, integrating cross-sectorial challenges (e.g. energy, water, climate, biodiversity, health).

The circular bioeconomy as a way to sustainability

Potentials and requirements of realising sustainable circular bioeconomic systems (SCBS)

"The bioeconomy provides numerous products, services and systems that are produced and/or used in a wide range of economic sectors. In addition to the traditional sectors of agriculture, forestry and fisheries, the production of food and animal feed, wood processing for construction, furniture and paper, as well as natural fibre processing or wastewater treatment and environmental technology, the sectors of organic chemistry (e.g. chemical-pharmaceutical industry, plastics industry), mobility and energy generation (electricity, heat), which today still consume fossil carbon and energy sources, as well as the (re)extraction and processing of important chemical elements (metals, phosphorus, nitrogen) are increasingly being integrated into the bioeconomy. In the area of the use of resources from agriculture, forestry and processing sectors, work is being done in particular on the development of processes that enable the full use of limited natural resources in cascade and combined use. In addition, conversion and upgrading processes are developed to produce new materials with functional properties. Carbon sources for carbon-dependent organic chemistry are also being produced[13]".

A circular bioeconomy aims to minimise resource depletion, promote regenerative practices, prevent overexploitation of natural resources, and encourage reuse and recycling of unavoidable by-products, losses or waste[14]. Future SCBS will produce food, feed, biomaterials, biomass and derived products in partnership with nature. New ways of production and consumption must be found that respect the ecological limits of the planet[15,16]. Locally tailored solutions are needed to realise the potential of SCBS, strengthening the resilience of local and regional food supplies while sustainably using natural resources close to the source. Ecological boundaries need to be explored at different spatial scales. The knowledge base and understanding of specific SCBS areas must be based on the collection of relevant data, the generation of better information and systematic analysis, leading to tailored advice on sustainable management options for the primary sector and the empowerment of local communities[1,16,17]. We need to develop and apply innovative technologies and management strategies to harness the potential of natural systems and processes efficiently and sustainably. This applies equally to conventional, integrated and organic production, which should increasingly be practised in line with nature's capacity, supported by the use of digital precision farming technologies.

Food and feed production is a core aspect of SCBS, also with regard to global food security and health. Sustainability and resilience of food systems are highly relevant for providing healthy food, advancing SCBS and addressing pandemic challenges. To ensure food security, agri-food systems need to be sustainable and resilient to environmental and economic crises in a multi-stakeholder approach covering the entire agri-food system from primary production, post-harvest handling, food processing, retail and distribution, packaging, waste and recycling, consumption and health. As defined during a Leibniz workshop in Berlin 2022, June 06-07, organised by the interdisciplinary Leibniz Research Network "Green Nutrition - Healthy Society", Sustainable & Resilient Nutrition (SRN) is healthy nutrition within regional and global environmental limits, respecting animal welfare and fair food environments. Such environments support socio-cultural identification, participation and empowerment.

The high level of complexity of agri-food systems and their interactions with other related systems requires that challenges be addressed decisively through a systems approach. The concept of such a systems approach is already well established in international discourse - including much of the research community - and has also found political expression in the UN Programme of Action. The considerations underlying the concept of agri-food systems in international discourse also include the use of agricultural products for energy and materials.

Specific challenges of controlling and managing bioeconomic systems

SCBS are at the interface of biology and technology. This implies a number of specific characteristics that lead to fundamental differences compared to traditional industrial systems and have many and far-reaching implications for process control and system management: SCBS host a variety of interacting living organisms, i.e. micro-organisms, plants and animals involved in the production and conversion of biomass. SCBS involve the need to control natural processes, i.e. to harness spontaneous biological, chemical and physical processes for specific purposes. This tailored use is limited by the fact that (i) the natural processes are often stochastic and thus affect production externally and with limited predictability, (ii) relevant information on the process status is insufficient, leading to incomplete knowledge of the initial situation for further management activities, and (iii) the mechanisms of action are not fully understood, limiting the predictability of the effects of potential management options on system behaviour. In addition, process control in SCBS covers a wide range of response times, from real-time to long-term responses, making it even more difficult to understand the processes and systems. SCBS require a large number of alternative actions to respond to the large number of different system states that can occur. Overall, there is a high level of complexity inherent in SCBS, while the knowledge and technologies to operate and manage this complexity have been inadequate to date.

Need for systemic and technological innovations

With the promotion of the human right to adequate food and sustainable and healthy diets, and the need for renewable resources in other parts of the economy, primary agricultural production has a key role to play, directly or indirectly, in addressing many of the global challenges. Circular production systems, including crops and livestock, can provide valuable regulating and supporting ecosystem services through their direct interaction with land, vegetation, soil and habitat. Livestock and crop production need to be (re)connected to achieve synergies and higher performance based on new feed sources, biofertilisers and soil fertility. Improved system-level quantification and identification of mechanisms of transition from linear to circular bioeconomy is needed. Integrated modelling approaches, multi-criteria assessments and policy analysis tools need to be strengthened. Transformative processes involving the latest innovation methods such as design thinking, cross-industry innovation, crowd sourcing or hackathon approaches are needed to effectively integrate crop and livestock production into the SCBS.

The Horizon Europe Strategic Plan 2025-2027[18] clearly supports these needs and identifies R & D as a key enabler for transformative changes in the economy and society. In addition to the necessary transformative policies, inclusive and sustainable productivity growth and digital technologies are identified as key to addressing today's global challenges while respecting planetary boundaries.

Currently available technologies will not be sufficient for the transformation of agri-food, industrial and energy systems, but both technological and systemic innovations are needed to achieve the transformation towards SCBS. Technological innovations are a sine qua non for the required comprehensive transformation of bio-economic systems. They are an essential means to support the systemic changes and thus to address the global challenges. Concurrently, technological innovations can have significant environmental, economic and social impacts and thus trigger systemic change. Therefore, technological innovations must always be considered, analysed and assessed in a systemic context.

Systemic innovations

In the light of the Grand Challenges outlined above, there is a clear need to rethink the role of agriculture, so that the current scope of agriculture – the production of biomass – is broadened to include the perspective of health protection and promotion, and so that agriculture is seen as an integral part of **comprehensive One Health approaches.** In this way, agriculture will become an essential element of health protection, and the importance of agriculture significantly increases. A systemic shift towards healthy and sustainable diets is required, characterised in particular by a reduction in the consumption of meat and other livestock-based products in many countries, and a shift towards more plant-based diets with high nutrient retention and, in addition, meeting protein needs from alternative sources such as insects or algae. The **protection of biodiversity** will be supported by key systemic innovations for closing material cycles, diversification, reducing the use of synthetic pesticides, establishing small-scale structured and differentiated land use, regional adaptation of livestock densities, reconnecting crop and livestock production, dedicating sub-areas for biodiversity conservation, integrating microbial diversity and valorising biodiversity. Important areas for systemic innovations for **climate change mitigation and protection** are dietary changes, the closing of material cycles, the rewetting of peatlands and the regional adaptation of livestock densities. Systemic innovations for **adaptation to climate change** are diversification, breeding and the management of water, soil, crops and livestock. **Closing material cycles** through greater integration of crop and livestock production, the food sector, biomaterials and bioenergy production, and comprehensive residue management is needed for waste-, loss-, and emission-minimised provision, sequential use, and recycling of biomass and the elements it contains. Major systemic innovations are needed for regional adaptation of crop-livestock systems, rewetting of peatlands, reduction of synthetic fertilisers through organic fertilisers and precision fertilisation. **Diversification** is one of the most important strategies for strengthening the resilience of bioeconomic systems. Diversification should be understood multi-dimensionally in terms of (i) biological diversity: broadening the range of plant and animal species used in interaction with the microbiome, vegetation, fauna and landscape, (ii) economic diversity: broadening the range of products and producing enterprises, and (iii) social diversity: diversity of actors and their relationships. Significant systemic innovations are needed in all three dimensions and can only be achieved through their interaction.

Technological innovations

Current agricultural and industrial systems rely on technologies designed for a different era. To achieve true sustainability, disruptive technological innovations across the entire chain are needed. Among these, digitalization and bioengineering stand out for their transformative power and flexible integrative approaches, especially when combined.

Digitisation: Advancement in technological innovations are needed in sensor development, data storage, transmission, processing and analysis, automation and robotics to better deal with the high variability and stochasticity in SCBS. Thus allow to work with a high degree of spatial, temporal and individual differentiation, and to better understand and control processes with medium- and long-term effects. The development of digital twins for sensor- and model-based, largely automated process control in many subsystems is identified as a key area.

Artificial intelligence, image processing, and other Data Science related techniques will unlock new methods to analyze the vast and diverse data generated by bioeconomic systems, supporting various research areas and strengthening the overall impact of data science within ATB. It also plays a crucial role in developing "soft sensors" and control systems for automated production. ATB boasts a long history in developing sensors, focusing on creating machine-readable indicators and integrating them with control systems. Examples include non-invasive fruit quality detection, remote sensing in plant production, and in-storage monitoring systems. Additionally, control system development is a key focus in areas like plant production and drying technology to allow for continuous optimisation and systematic development of value chain that would help build digital twins (DTs) in agricultural systems.

DTs are promising tools to address the specific challenges of process control in SCBS. They provide high-resolution information about the processes, obtained with modern sensors and processed with innovative methods, generate model-based predictions of future process states and implement automated reactions or recommend options to human actors. By collecting and analysing the data over longer periods of time, they can also contribute to deeper understanding of processes and systems.

ATB's vision is to leverage sensor and actuator technologies as a key connecting element in future research activities. This includes (1) Reliable, machine-readable indicators: Developing methods that allow to capture data accurately and efficiently; (2) Non-invasive measurement and sensor networks: Combining intrinsic data from plants, animals, products, processes, and the environment for a holistic view; (3) Soft sensors and evaluation algorithms: Extracting meaningful insights from sensor data through advanced data fusion and analysis; (4) Control and actuator systems: Utilizing the extracted information to automate and optimize production processes. This combined approach, linking data and sensor technology with modelling and advanced machine learning methods, paves the way for developing scalable, robust and real-time interactive DTs.

Microbiome (bio) technology & management. The work in microbiology has been strategically developed towards microbiome(bio)technology & management, which are emerging as game-changers for building SCBS. Microbiomes are crucial for the transition of agriculture to a circular bioeconomy and for the one health approach. The minor strategic extraordinary item of expenditure "Microbiome Management in the Circular Bioeconomy" will come into force in 2025. The aim of future research in this area is the knowledge-based control of highly diverse SCBS; examples of microbiome-based technological developments ATB strives for include plant protection products, probiotics and fertilisers as well as biomarkers and sensors.

ATB vision, mission and core competences

ATB answers to the global challenges and need for innovations identified in the first chapter with its innovative research set out in ATB's vision and mission.

Our vision

A circular, diverse, innovative and sustainable bioeconomy produces healthy food for all, operates on the basis of renewable raw materials and facilitates the realization of One Health for humans, animals and the environment.

Our mission

The Leibniz Institute for Agricultural Engineering and Bioeconomy is a pioneer and a driver of bioeconomy research.

We create the scientific foundation to transform agricultural, food, industrial and energy systems into a sustainable bio-based circular economy.

We develop and integrate techniques, processes and management strategies, effectively converging technologies to intelligently crosslink highly diverse bioeconomic production systems and to control them in a knowledge-based, adaptive and largely automated manner.

We conduct research in dialogue with society, policymakers, industry and other stakeholders. – knowledge-motivated and application-inspired.

Core competencies of ATB

The **development of new methods and technologies** in **the programme areas of Diversified Crop Production, Individualised Livestock Production, Healthy Food, Multifunctional Biomaterials, and Integrated Residue Management** and their **integration into holistic approaches** will continue to make a major contribution to the success of the transformation to comprehensive SCBS. These developments span from basic research on identifying mechanisms at process level, continue with measuring relevant process parameters, modelling processes and their interactions and finally managing them to achieve sustainable, resource efficient site-adapted, productive and profitable production of food and biomaterials.

ATB recognises that achieving SCBS requires the transformation of existing linear value chains into diversified, interacting and interdependent production systems involving complex networks of processes, (by)products, functional ingredients and residues that can be cascaded for multiple uses. **ATB's USP (unique selling point)** is to create the knowledge base and develop appropriate solutions with a wide range of interdisciplinary expertise, from data science to agricultural engineering, from sensor technologies to microbiological and physiological processes, from embedded programming to process modelling and simulation, and from electronic hardware design to life cycle assessment, legal aspects and transdisciplinary integration of practitioners.

The development and implementation of ATB´s novel approaches are carried in collaboration with stakeholders following the "research – impact – cycle". ATB's active contributions to and leadership of international fora and its intensive collaboration with a wide range of stakeholders (e.g. farmers, consumers, policy makers, industry) identify future challenges, outline proposals to pave the way for solutions, and elaborate research needs that form the basis for research projects. In doing so, ATB contributes to the creation of new knowledge in close cooperation with national and international partners. This knowledge is then fed back to the policy and stakeholder bodies.

Diversification and individualisation, digitalisation, microbiome management, and **systems modelling** are the pillars on which ATB plans to develop substantial contributions to solving the grand challenges outlined in Chapter 1. ATB aims to further develop and integrate digital models into fully-functional digital twins in the core research areas for the realisation of a sustainable SCBS. Due to the special characteristics of SCBS, the development of digital twins for process control is particularly challenging, but at the same time offers considerable potential. With the modular approach to (sub-)system modelling and assessment and the successful implementation of relevant digital twins, combined with the technical expertise available at ATB, the institute will take a leading international role in the modelling and assessment of crop and livestock production, residue management, biomaterials and healthy food and their integration into SCBS as well as the development of the necessary hierarchical digital twins structures and community connectivity of complex systems.

The **Leibniz Innovation Farm for Sustainable Bioeconomy (InnoHof)** provides a comprehensive platform for inter- and transdisciplinary research on innovative solutions, enabling the exemplary realisation of our vision of a sustainable and circular bioeconomy from lab/pilot plant to plot to production scale on the farm. The InnoHof combines existing infrastructure at ATB and, where appropriate, at partner institutions, with new state-of-the-art facilities, together with office and communication space. New facilities include for instance insect rearing and algae cultivation, non-thermal and thermal food processing, material use of biomass, and integrated residue management including bioenergy production and innovative concepts for renewable energy use on the farm. With the new facilities, ATB established an additional campus next to its long-standing, independent, agricultural cooperation partner, the Lehr- und Versuchsanstalt für Tierzucht und Tierhaltung e.V. (LVAT) in Groß Kreutz. LVAT contributes its arable land and grassland (940 ha, as of 2023) and, where possible, barns for various livestock species for the implementation of research activities in a fully operational farm. Its so-called welfare dairy barn is already equipped with extensive sensor and measurement technology for barn climate and animal welfare research. These were designed and are maintained by ATB and provide fundamental data for use in other infrastructures such as the wind tunnel. Cutting-edge technologies and novel management strategies are implemented, tested, analysed and further developed in the innovation areas of diversification, digitalisation and microbiome management. The InnoHof with its subsystems and as a whole will serve as a physical object for the development of digital twins at all levels of process control.

This is further supported by the Joint Lab ‘Artificial Intelligence & Data Science’ (Joint Lab KI & DS), launched in April 2023. Application-specific Data Science and AI technologies and direct transfer are the core idea of the Joint Lab KI & DS with a focus on optimising, increasing efficiency and automating agricultural processes. All research is conducted as co-creation approaches including relevant societal, political and industrial players from the onset. The InnoHof as focal point for mission-driven inter- and transdisciplinary translational research contributes to ATB´s USP. It enables the exemplary realisation of ATB’s vision of a SCBS following the One and Planetary Health approach by means of a model farm and in other contexts as a Living Lab.

Organisation of ATB research in five programme areas

Research work at ATB is organised in five programme areas (PA) (Figure 1) on an interdisciplinary and cross-departmental basis. The PA reflect the five bioeconomy domains, ATB is active in. This highly innovative approach is a consequent further development of the former ATB research organisation to contribute to solving the challenges outlined in Chapter 1. ATB's five PA organise their research into individual roadmaps, which are regularly updated and linked to ATB's overall research strategy. Each of these roadmaps has a long-term goal and a step-by-step approach to achieving it.

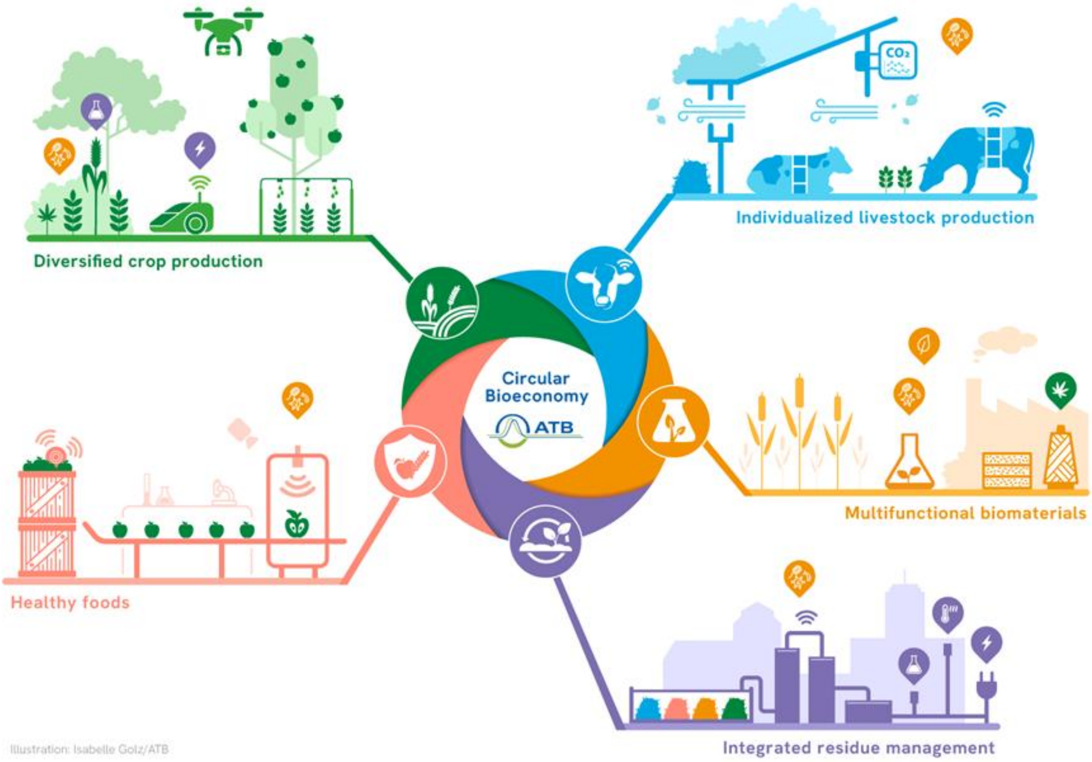


Figure 1: The five programme areas of ATB and their contribution to circular bioeconomy.

Diversified Crop Production

The PA **Diversified Crop Production** postulates that the crop production of the future will be integrated into the SCBS. It produces plant biomass for a healthy diet for all people and for an industry without fossil raw materials, and recycles biogenic residues in closed cycles. Future crop production will be diverse and resilient. It will promote biodiversity, be flexible and adaptable, with a variety of products, crops and management practices. The crop production of the future works with minimal use of external resources, conserves natural resources, is climate-friendly, ensures a fair income for farmers and contributes to the common health of humans, animals and the environment. To achieve this, PA DCP has as its long-term goal the development of concepts and technologies for highly diverse crop production, using digitalisation and microbiome management as key tools.

The PA Diversified Crop Production (PA DCP) develops technologies to analyse the status of crop stands, fruit and soils in order to adapt the management practices - site specific or tree individual - to the natural requirements. It analyses the impact of crop production on the environment as well as the impact of climate change on the crop production, in order to derive resilient, environmentally sound, highly diversified agricultural systems that are an integral part of SCBS. This involves the development and control of highly complex production systems, where automated machines and digital tools for sensing and analysis become a necessity. Technologies include microbiome management, life cycle assessment, scenario simulation, sensor systems, data analytics, explainable artificial intelligence and knowledge representation, automated process control and field robotic as well as digital twins. Key to all automated environmental sensing and process control tasks is the availability of machine-readable information, with machine readable sensor-indicator-systems as the functional core. New holistic farming strategies require new indicators, especially environmental or biodiversity indicators, which have not been production targets of farming systems so far. The long term strategic goal is to implement 'diversity as a management objective' in agricultural production systems. This requires as a key task the development of sensor-indicator pairs for the holistic assessment of crop production systems.

The PA DCP focuses on methodological issues of intelligent image analysis and the development of smart sensors for the digital recording of environmental conditions and plant status. These digital methods are expected to make a decisive contribution to the further development of sensor-based process control and automation — a prerequisite for the complex control systems of SCBS. Securing machine-trained knowledge for future use by human experts will be a challenge and focus for the coming decades. To achieve these goals the PA is strongly involved with the Joint Lab KI & DS. It is a fundamental player in the InnoHof and the Field Lab for Digital Agriculture in Marquardt, providing key contributions to these endeavours.

The PA DCP focuses on (i) *Soil Health* (ii) *Plant Health*, (iii) *Digitization*, and (iv) *Holistic Cropping Systems. Soil Health* develops tools for sensor-based characterisation of soil fertility parameters, and applies them to the long term vision of sustainable use and improvement of the soil. It focuses on monitoring all soil related information relevant to a sustainable crop production. In addition to chemical and physical proximal soil sensing techniques a strong focus will be on the development of biological sensing systems to analyse microbiological soil health parameters. Further systemic approaches will correlate soil sensor readings with yield data to derive soil fertility from yield relevant parameters. *Plant Health* pursues the vision of securing the food supply by strengthening plant and crop health. It focuses on precise monitoring techniques to enable environmentally friendly crop protection and product quality. Information on crop, plant, product and pest status includes microbiological characteristics and biodiversity monitoring. Current measurement approaches include in situ, proximal and remote sensing, with a strong focus on optical sensor systems, supported by microbiological sensing. *Digitization* follows the vision of providing control systems and automated machinery to support diversity in agriculture as a management objective. It focuses on the identification and development of assistance systems, automated applications, and field robotics tasks and uses the latest simulation and Internet of Things (IoT) technologies to develop digital twins in order to develop and improve highly automated in field sensor systems, field machinery and field robotics. *Holistic Cropping Systems* applies the long term vision of assessing SCBS from the source to the sink. It focuses on identifying the impact of agricultural management practices on greenhouse gas (GHG) emissions, water productivity, and Information and Communication Technology (ICT) application, analysing rebound effects and seeking a better understanding of microbial processes. In addition to Life Cycle Assessment (LCA) and modelling, knowledge representation and digital twins are key techniques.

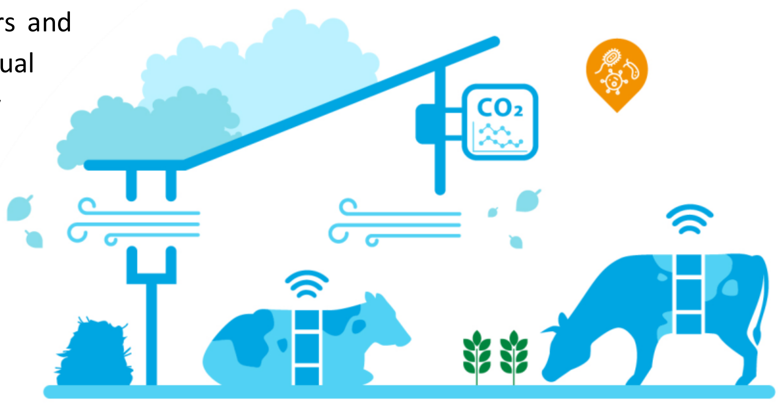
Individualised Livestock Production

The PA **Individualised Livestock Production** combines research approaches in inter- and transdisciplinary collaboration within ATB and with external partners with the aim of integrating sustainable solutions for livestock production systems into holistic SCBS for global food and nutrition security with low negative environmental impact. Concepts for sustainable livestock production are supported by smart and high-tech solutions using digital technologies and integrating change processes (including climate and society). Detailed understanding at the process level is fed into modelling approaches with the aim of providing a toolbox for innovative, region-specific and flexible solutions that combine the needs of farmers, consumers and the environment. The InnoHof provides excellent opportunities and further stimulates research and implementation of livestock-related challenges.

The PA Individualised Livestock Production (PA ILP) analyses site and animal specific processes to advance knowledge-based agricultural production, as part of holistic SCBS. The research results will provide the basis for adaptive process control mechanisms and management strategies for an environment-friendly, health-promoting, animal-friendly and profitable agriculture with high system-efficiency to meet future requirements. Scientific objectives are the definition of indicators for animal welfare, health, and emissions, the development of related sensor technologies and the modelling of the interactions. The PA ILP addresses major societal challenges such as nutrient losses and pollution, reduction of GHG emissions and implementation of climate change adaptation strategies, as well as concerns for environmental, human and animal health and animal welfare. It develops solutions from basic scientific insights to practical implementation. The backbone is inter- and transdisciplinary cooperation within ATB and with external partners aiming at integrating sustainable livestock production processes into holistic bioeconomic systems.

The PA ILP focuses on (i) *Animal Welfare and Livestock Systems*, (ii) *Barn Climate and Emissions*, and (iii) *Assessment of Livestock Production Systems*.

Animal Welfare and Livestock Systems will further refine the development and use of innovative sensors and non-invasive methods for animal individual recording and analysis of animal traits for early warning systems for animal stress and health. In the coming years, the use of data science, artificial intelligence and innovative methods will support the fusion of sensors and the automated assessment of animal health and welfare. Building on the intensive research into heat stress in dairy cows in recent years,



the findings will be used to identify heat stress individually for each animal and to enable early human and/or technological response.

Barn Climate and Emissions will continue its research to develop measures to measure, characterise and predict the dynamics of environmentally harmful and climate relevant gases, infectious bio-aerosols and multi-resistant pathogens within the three-pillar-model. On-farm measurements in various housing systems and basic research in the unique infrastructure of the "atmospheric boundary layer wind tunnel" will an create an extensive data pool. The focus will be on the characterisation of novel housing systems, mitigation measures, and emission measurement methods. Digital technologies such as high-performance Computational Fluid Dynamics (CFD) simulations, and the establishment of data science and highly scalable numerical methods will enable advances in the process understanding of gas and particle transport.

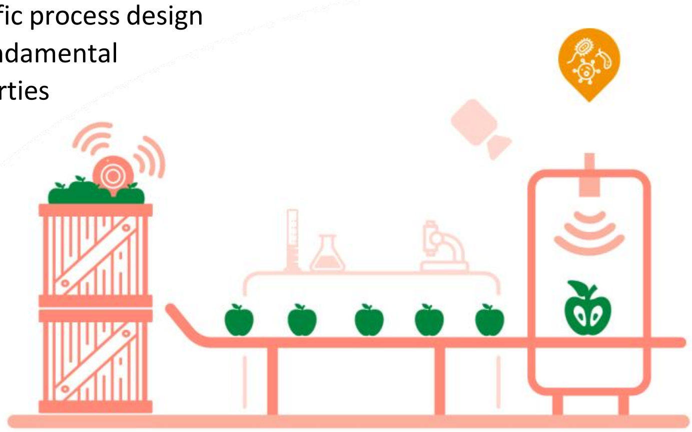
Assessment of Livestock Production Systems sees integrates data into individual and flexible concepts for sustainable livestock production through modelling, systems analysis and multi-criteria assessment including the quantification of trade-offs and synergies. Research results will feed directly into active contributions and leadership roles in FAO, United Nations Economic Commission for Europe (UNECE), Intergovernmental Panel on Climate Change (IPCC) and other international bodies.

Healthy Foods

The PA **Healthy Foods** explores the design of sustainable processes that have a targeted positive impact on the food biosystems involved and implements new monitoring techniques that take into account nutrient profiles and microbiomes along the post-harvest chain, which is used to develop advanced and "smart" process settings and technologies. The development of the tailor-made physical, physico-chemical and/or biological processes takes into account important food ingredients, desirable (the edible microbiome, probiotics) or avoidable (pathogens) microbial communities, product characteristics as well as production-related working conditions and environmental influences. The PA HF strictly follows the principles of Quality by Design (QbD) in the diagnosis, optimisation and in the development of physical and soft sensors, as well as control systems. Identifying the design requirements for digital twins to meet the prerequisites for integration into processes control will be the central aspect of the work in process development. Requirements for self-optimising functions within the digital twins, other sub-systems and the overall system, integration of high-dimensional and sparsely populated information using machine learning approaches will be investigated and implemented exemplarily. The PA HF valorises by-products of food and feed processing, develops circular processing concepts and identifies sustainable processing routes and techniques by analysing product-process interactions, and the quality and safety of alternative products.

A resilient and sustainable nutrition concept comprises physiologically balanced, plant-focused diets (fruit and vegetables) including re-introduced (underutilized) site-specific plant species and varieties (e.g. legumes, pseudo-cereals, perennials), emerging alternative food resources (e.g. marine organisms, insects, cellular agriculture) as well as innovative technologies (e.g. non-thermal processing techniques) and smart processing systems emerging from traditional processing technologies (e.g. drying of bulk products, novel process set-up designs), aiming at both resource efficiency and improved product quality.

The PA Healthy Foods (PA HF) aims at the targeted integration and innovative orientation of the research capacities of the PA, taking into account regional, national, European and global research. The current state-of-the-art will be furthered through fundamental research to achieve the goal of minimising the postharvest losses and increasing product quality based on optimised and advanced product-specific process design for future food systems as part of SCBS. Based on fundamental expertise in the main working areas are: product properties and in situ sensors, microbial communities, dynamics thermal and non-thermal processes, as well as packaging and storage systems, important research data on the respective product-process interactions will be generated using the specific infrastructure (field sensor conveyor for phenotyping, fresh produce laboratory, innovation lab for proteins, microbiology laboratory, smart drying pilot plant as



well as the storage and packaging pilot plant). Furthermore, existing data will be analysed and integrated into future research using data science methods.

Starting from the adapted, specific cultivation of different food resources (plant, marine and animal related, in close collaboration with all other PA and up to the consumer level, information on product-process interactions will be sought for the best possible design of the entire post-harvest chain. Suitable parameters for in-situ monitoring of quality indicators of food materials along the supply chain will be further investigated, in particular using optical methods. The in-situ analysis of perishable foods will be advanced by means of multispectral light detection and ranging laser scanning, point spectral photometry, and thermal imaging in the field and in postharvest (hyperspectral imaging, front-face fluorescence, laser-induced multispectral backscattering analysis, Raman microscopy, time-resolved fluorescence); during storage, during and after thermal or non-thermal processing, during shelf life. Targeted process control also requires the early and specific detection of microbial contamination, which call for particularly innovative methods of detection in the post-harvest area. Cultivation-dependent and cultivation-independent approaches based on the analysis of microbial DNA sequences will be further developed as a basis for testing the targeted influence on microbial diversity. The characterisation of microbial communities and their dynamics along the process chains from the substrate to the product is expected to contribute to the targeted use of decontamination processes for inactivation of pathogenic microorganisms and the promotion of desirable microorganisms. Furthermore, the promotion of beneficial microorganisms will be a core aspect of the development of smart food processes. The PA HF will further expand the expertise gained in recent years in non-thermal process applications. Upscaling and the transfer to industrial application will be an important focus of the research. The newly established laboratory platform will enable fundamental, large-scale experiments with pathogens in model processing chains, particularly with regard to the resulting microbial population dynamics.

The product information gained will be integrated into agronomic models as and control systems to develop of digital twins of both products and processes as well as their combination. Increased emphasis will be placed on the use of in-situ product data in the modelling of post-harvest processes and the linking of the two domains, e.g. through the development of digital twins. In addition to fruit and vegetables, other novel or less considered food resources (hemp, algae, insects, etc.) are investigated and a holistic value-added approach for future SCBS is developed, taking into account the quantification and characterisation of components such as proteins, lipids and polysaccharides during post-harvest handling and processing. Physics based and data driven models will be combined in a digital twin. Basic research will, therefore, increasingly focus on the investigation of relevant, quality-determining constituents in order to develop and optimise innovative, gentle and smart product-specific processes. The novel combination of the process models with measured ingredient specific reaction kinetics and microbial population dynamics will be further developed.

Multifunctional Biomaterials

The PA **Multifunctional Biomaterials** is closely linked to the new concept of biorefineries, which means that the sustainable production of biomass and its subsequent processing does not focus on a linear model, but aims to establish closed loops. The research activities of the PA MB continue to move towards fundamental research related to biomass processes at the level of biomass supply and potentials for carbon storage, biomass pre-treatment, processing and conversion. At the biomass supply level, the carbon storage potential of lignocellulosic crops will be further investigated in order to optimise sustainable agricultural production chains. Following the process chain, further research will focus on the effects of thermo-mechanical processing of lignocellulosic crops, e.g. on fibre morphology, fibre bonding and water holding capacity. At the level of bioconversion, new strategies for succinic acid production are being developed. The biological route to the production of organic acids, including succinic acid, opens up new avenues for their sustainable production and biosuccinic acid may have the potential to increase the shift from fossil-based plastics to renewable products. Microbiome-based concepts will be used to develop new products together with probiotics.

The PA Multifunctional Biomaterials (PA MMB) aims to develop site-specific technical and process engineering solutions for the sustainable production of biomass in agriculture and its further processing for resource efficient use as biomaterials. It addresses major societal challenges such as the global demand for biomass as a substitute for fossil resources, the reduction of GHG emissions from biomass production and processing chains, the valorisation of agricultural by-products and residues for material use as well as the implementation of climate change adaptation strategies in non-food crop production in agriculture. The PA MMB focuses on the establishment of closed material cycles, in particular closed carbon cycles, to promote the use of biomaterials as a carbon sinks. Consequently, the use of solid agricultural biomass and residues for the implementation of efficient biomass energy with carbon capture and storage (BEECS) strategies for carbon neutrality in 2050 is also in the research focus. The scientific objectives range from deepening the fundamental understanding of physical, chemical and biological processes during biomass supply, pre-treatment, processing and conversion, to optimising whole process chains on a practical scale. .

The PA MB focuses on (i) *Process Engineering for Energy Crops*, (ii) *Process Engineering for Fibre Plants*, and (iii) *Biobased Chemicals*. All these aspects are closely linked and collaborate with other research areas, such as residue management or food production. The research carried out along the entire value chain for the supply of bio-based fibre raw materials leads to technical applications. A particular challenge for

the development of resource-efficient fibre production technologies is wide range and the high variability of the different plant material properties. Therefore, it is necessary to determine and model environmentally or technically induced changes in these properties. Conversion processes during growth, but especially during harvesting, drying or field retting and subsequent processing, require appropriate methods to characterise the material and structural composition of raw materials and intermediates. New methods are being developed to determine specific morphological, gravimetric or mechanical properties. From this, effective operating principles for technical equipment can be derived as a basis for the development of novel solutions for individual process steps up to new process lines for fibre crops and alternative lignocellulosic biomass from agriculture. Research will also focus on sustainable agricultural production and processing chains for lignocellulose from short rotation coppices, agroforestry systems and paludiculture. In the coming years, the use of data science, artificial intelligence and sensor networks will help to resolve the conflicts between the conservation of natural resources, the need to adapt to climate change and the efficient production of biomass in agriculture and the subsequent production of biochemicals. Digital twins of these systems will support optimisation of field, process design and management, while enabling carbon flux accounting. New process lines for products from rewetted peatland biomass form the basis for the implementation of national and international peatland restoration strategies, will significantly reduce carbon emissions from agriculture and reactivate peatlands as a global carbon sink. In addition, the efficient and cost-effective production of bio-based chemicals is a crucial step in the transition to a bio-based economy, which will be demonstrated at the InnoHof, where a dedicated infrastructure will be established. The production of bio-based chemicals is based on the use of renewable resources, including, but not limited to, lignocellulosic biomass. Any type of biomass, including industrial by-products and municipal solid waste, containing simple sugars can be converted by microbial fermentation into a specific product, such as lactic or succinic acid. Platform chemicals play a crucial role in the formation of new and functional biomaterials in many areas, such as food packaging, the automotive sector, agricultural or medical applications, printed electronics and others. The sustainable production and value-added processing of biomass through novel and advanced technologies is the objective of this project to better explore the environmental and economic potential of biogenic resources in terms of process efficiency and product quality.

Integrated Residue Management

The PA **Integrated Residue Management** sees residue management as an integral part of SCBS. It works on the sustainable valorisation of residue streams through robust and flexible residue utilisation processes, carries out microbiome analyses for in-depth process understanding, process monitoring and control, develops a digital twin including sensor- and model-based process control, and incorporates results into system modelling and evaluation of interaction with the environment. Biogas production, as an integral part of the SCBS, is closely linked to other production systems. Research activities will take further steps towards basic research related to locally and regionally available biogas feedstocks, alternative residual biomass types, their supply, pre-treatment and bioconversion as coupled or cascaded uses. This will contribute to the development of multi-product systems, closing nutrient cycles and minimising the risks associated with increasing biomass flows. The assessment of specific residual biomass types, supply and bioconversion processes provides modules for modelling and evaluation of SCBS.

The PA Integrated Residue Management (PA IRM) focuses on the recycling and sustainable use of residual biomasses to improve resource efficiency, close nutrient cycles, increase independence from fossil resources and reduce risks and environmental impacts. Residual biomass comes from a wide variety of production processes and is returned to the biomass cycle. The diverse origin of biomass residues and their occurrence at the end of the cascade leads to increased demands on final conversion and utilisation technologies, as biomass residue and waste streams are often largely inhomogeneous, may pose risks, contain impurities and unfavourable components, and occur in varying quantities and qualities. Consequently, the PA IRM aims at a thorough characterisation of residual biomasses using advanced sensor technologies, the development of robust and highly flexible conversion technologies to enable efficient and environmentally beneficial treatment of a wide variety of biomass residues, combined with an increased and demand-driven supply of valuable products with specific parameters or qualities.

The PA IRM brings together research activities on residue management, including biomass characterisation, supply, processing and risk mitigation, residue conversion and product utilisation. In order to facilitate residue-adapted process design and a wide range of product formation, different conversion processes will be advanced and optionally coupled. These include (1) biological conversion using macro-organisms such as insects or macro-algae, (2) microbial conversion such as fermentation for organic acid production or anaerobic digestion, and (3) thermo-chemical conversion such as pyrolysis, hydrothermal carbonisation or hydrothermal humification. The demand for process flexibility and targeted product formation will in future require the operation of conversion processes based on knowledge, information and automation.

Therefore, research activities will deepen the fundamental understanding of the physical, chemical and biological processes during biomass supply, pre-treatment, processing and conversion, and evaluate the interactions of the conversion process and products with the environment. Particular emphasis will be placed on the reduction of risks that may be associated with the re-cycling of residual biomasses. These include contamination, antimicrobial resistance, spread of potentially invasive seeds, climate-relevant emissions and pollutants. For microbial conversion processes, the microbiome will be further investigated in terms of its species-level composition, functions and ecological roles, using new sequencing technologies and co-occurrence and artificial neural network analyses to assess ecological diversity. This will prospectively lead to the identification of microbial system health indicators and contribute to improved process control. The PA IRM will further refine methods to characterise material parameters of feedstocks and products. An important sub-goal of the research is the adaptation and implementation of sensors to develop real-time measurement methods for continuous on-line determination of process and material parameters. Another approach to address the increasing need for process control is the development of predictive process models. Combined modelling of material conversion and microbial diversity is being pursued, e.g. using trait-based models and machine learning methods to map cause-effect chains and predict process performance or disturbances. The combination of improved measurements of process parameters and modelling will allow processes to be mapped as digital twins. Digital twins are expected to help control, manage and optimise process performance and improve reactor designs and control strategies.

A further focus will be on the up-scaling of residue management options and their integration into SCBS. This will be demonstrated at pilot scale at the InnoHof, where the infrastructure for advanced residue treatment and biological and microbial conversion technologies will be newly established in the near future. The different process variants and combinations will be evaluated using system modelling in terms of environmental, economic and social criteria in order to identify preferred residue management options. This will ultimately allow the integration of residue management strategies as an important part of SCBS.

The PA IRM is strongly linked with the other four PA as it works with the biogenic residues from cropping, livestock, food and biomaterial systems and can supply them with bioenergy, biofertilisers or nutrients, and soil amendments.

Strategic implementation of the research objectives

ATB has implemented several strategies, which are regularly updated. The individual strategies contain goals and measures for implementation and are in line with the medium and long-term strategic development goals of ATB's research strategy. It is important to continuously review the measures taken, to adapt them to changing conditions and to develop them further. Figure 2 provides a comprehensive overview of the strategies that support ATB's research strategy.

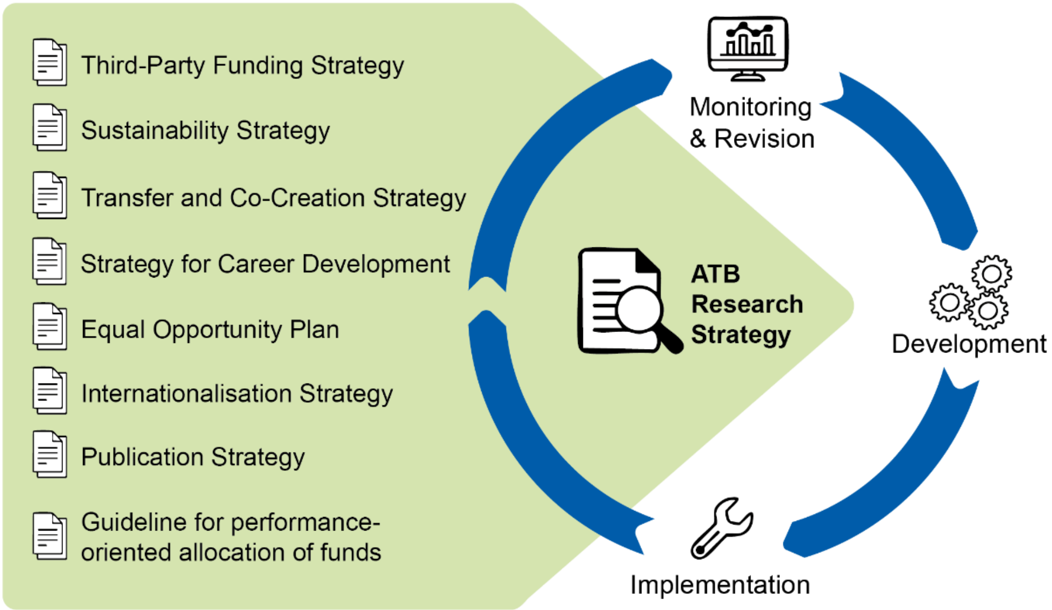


Figure 2: Overview of ATB's strategies.

The presented strategy was recommended to the Executive Board by the Internal Advisory Board on March 25, 2024 and was adopted by the Executive Board on April 9, 2024. It is the first strategy of its kind at ATB and comes into force on April 9, 2024.

Scientific Director

Administrative Director

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