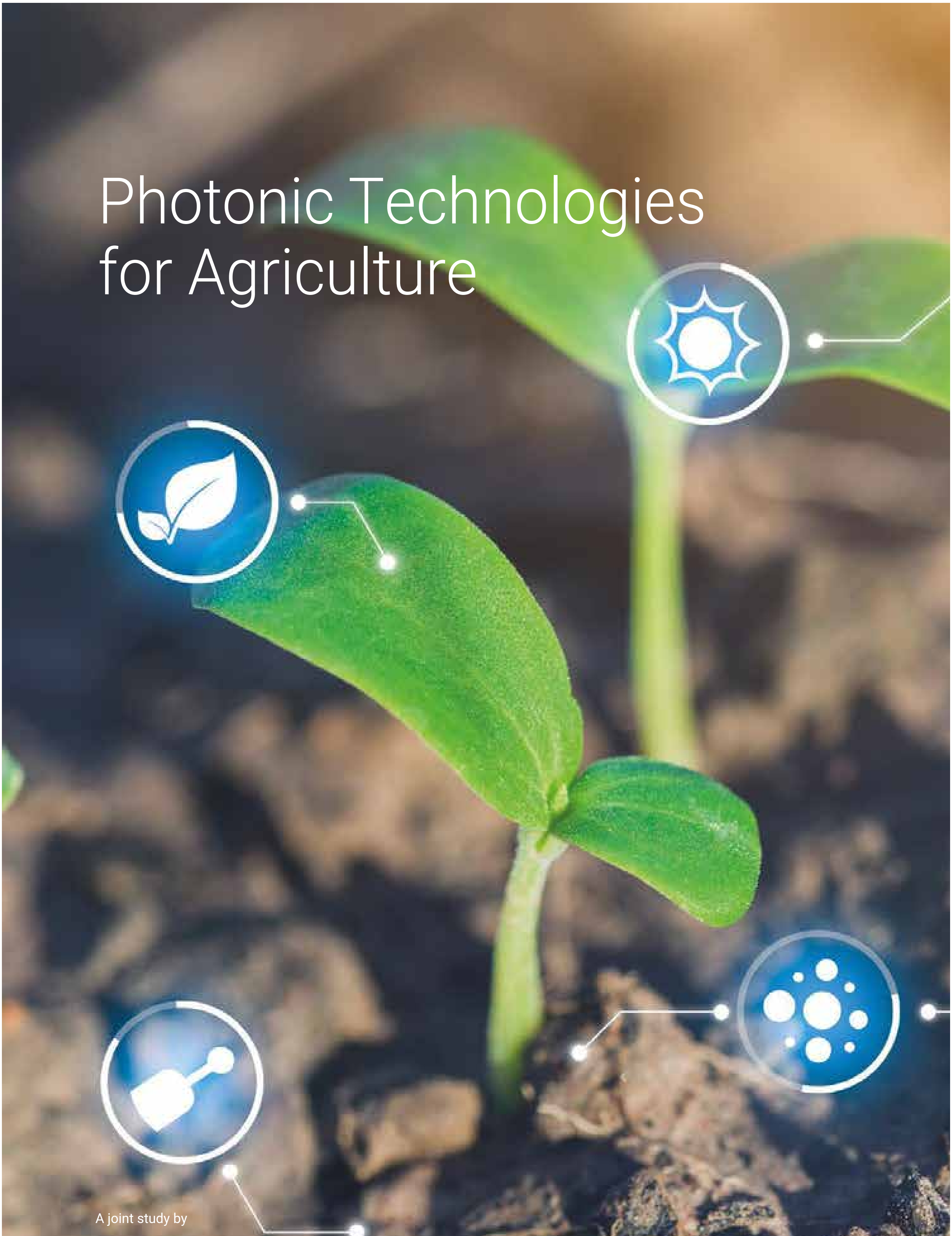
Photonic Technologies for Agriculture



A joint study by

Messe München

SPECTARIS
German Industry Association for Optics, Photonics, Analytical and Medical Technologies

Tematys
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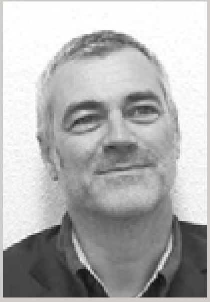

BENOÎT D'HUMIÈRES

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Benoît d'Humières graduated in Physics and Chemistry from the ESPCI Paris – PSL and the Sorbonne University. He is an expert in Optics, Electronics and Instrumentation for industrial and research applications.

In 1991, after some years of research at the University of Florida, he became an innovation consultant. He has run many marketing and technological studies for companies of any size and Research institutions. Benoît has also taught the marketing of photonic technologies at the Institut d'Optique-Graduate School (Palaiseau, France).

TEMATYS is an independent, medium-sized consultancy firm which focuses on studies and strategies in the areas of optics, photonics, sensor technology, imaging, quantum technology and their applied markets.

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The fourth agricultural revolution has begun

Jörg Mayer
CEO of the German Industry Association SPECTARIS

Photonics is a jack-of-all-trades. Those of us who work in the industry know its huge technological possibilities.

And In fact, photonics holds the key to solving the challenges of the 21st century. It can drive technological progress in a wide range of areas, such as sustainability, CO2 reduction, healthcare, changes in traffic volumes, autonomous driving, e-mobility, semiconductors, quantum systems, and communication.

In all these areas, photonics forms the indispensable basis for technological progress, without which the major challenges facing society cannot be solved. In this study, we would like to shed light on another field: food production.

Given the large number of people worldwide with poor access to sufficient or good food, there is a great need for technological solutions that are also sustainable and leave the paths of conventional agriculture with its immense side effects on the environment behind.
Photonics does not provide the one technological solution to this challenge, in the same way that, for example, improved battery technology was a game changer for electromobility. Rather, photonics provides building blocks of technical solutions that make agriculture more precise, faster and more efficient. Nor is there one user for photonics suppliers to focus on. The target groups are widely distributed along the agricultural value chain. For each user target group, it is worthwhile to be on the lookout now and in the coming years for technological advances that hold substantial efficiency gains. Conversely, developers of photonic components and solutions should get to know their users in the agricultural sector well and target them. The technological concept for the new and better solutions can be summarized under the term precision agriculture, which is based on four technology families: robotics and automation technology, imaging and sensors, digitization and big data analytics, and bioengineering. Photonics contributes to this by detecting, monitoring, understanding, and controlling. And, as you can already guess, none of these technology areas would be conceivable without photonics. Numerous solutions already exist, and yet precision agriculture is only in its infancy. The variety of ideas and innovations is enormous, just like the potentia. Annual growth of 15 percent is expected in the coming years alone. We hope you enjoy reading about an area that will have an impact on all our lives. We are still talking about the energy revolution, but soon we will be talking about the agricultural revolution.

JÖRG MAYER

CEO of the German Industry Association SPECTARIS

SPECTARIS
German Industry Association for Optics, Photonics, Analytical and Medical Technologies

A giant task – that can be solved with photonics

Dr. Reinhard Pfeiffer
CEO of Messe München GmbH

In traditional agriculture, farmers knew their farmland inside out. From experience, they knew where weeds sprouted, where plants often withered or where yields were higher. With this knowledge they could manually fertilize, sow, or apply pesticides with high precision.

But when it comes to feeding 11 billion people in the future, agriculture will have to operate on a completely different scale. Highly mechanized, with high working widths and high speeds, it will plow, harrow, sow, and fertilize its expanded croplands. Autonomous steering devices and robots will increasingly be used. In livestock farming, too, the trend is toward automation – be it in cleaning stables, feeding, or milking. In such highly productive agriculture, the close relationship with the soil and livestock is inevitably lost. And that is where photonics and its solutions come into play. Sensor and imaging technologies – mounted on drones, tractors, or machines – are replacing the watchful eye of the traditional farmer. They help transfer precision fertilization, seeding, and crop protection to data-driven high-performance agriculture.

This study demonstrates the huge potential of photonics for agriculture and its gigantic task of feeding billions of people despite climate change. It shows how photonics helps to increase productivity while using precision farming methods to manage with less fertilizer and pesticides by only using them where they are really needed. Sustainable progress in agriculture is also linked to photon-controlled broadband data networking, which ensures that all cultivation plans based on sensor and harvest data are optimally executed by highly automated machines in the fields. Finally, resilient crops will be essential in the face of tougher environmental conditions. With high-end microscopy and analysis equipment, photonics also has the right solutions up its sleeve here. LASER World of Photonics 2023 will give you an idea of what solutions such as these could look like.

Light is the key to feeding the world: in photosynthesis, of course, but also through photonic contributions to the highly productive and sustainable agriculture of the future.

DR. REINHARD PFEIFFER

CEO
Messe München GmbH

Messe München

Executive Summary:

Photonic technologies for agriculture

Agriculture harnesses the wonders of nature to feed the human population.

Yet 11 percent of humanity was undernourished in 2021, and 3 billion people could not afford a healthy diet in 2019. The world's population is expected to grow from 8 billion people in 2022 to 11 billion in 2100. That represents a 40 percent increase (source: see page 12). Agriculture will not be able to expand the area under cultivation at the same rate in order to provide everyone with sufficient food of the highest possible quality.

Agricultural land already accounts for about 37 percent of total land area. Around 33 percent of the world's soils are moderately to severely degraded. Soil erosion carries away 20 to 37 billion metric tons of topsoil annually, reducing crop yields and the soil's ability to store and distribute carbon, nutrients, and water. The rapid expansion of cities into less populated areas further narrows the available space. Deforestation is equally harmful, as it threatens biodiversity and increases greenhouse gas concentration in the atmosphere. The supply of more and more inputs, such as fertilizers, pesticides, or animal feed, is becoming less and less efficient, and the resulting pollution of the soil by excess inputs is becoming less and less acceptable to society.

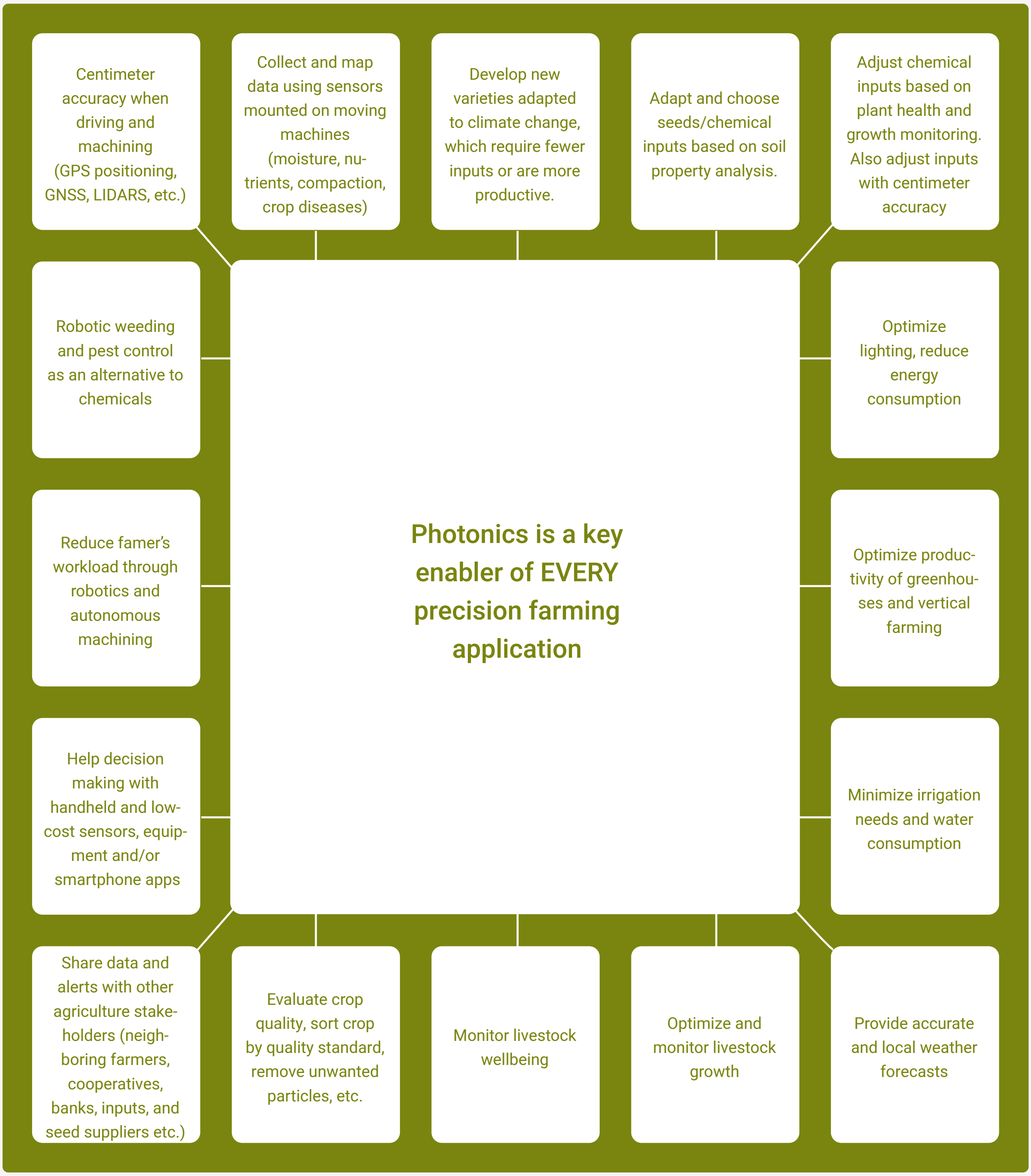
In addition, agriculture must not only dramatically increase yields, but also improve practices to stop soil degradation, reduce pesticides, maintain biodiversity, reduce green house gas emissions, and adapt to the effects of global warming.
The agriculture of the future will therefore have to rely on science, technology and the resulting new, innovative agricultural approaches such as precision farming.
Precision agriculture is an agricultural management concept based on observing, measuring, and responding to variations between and within fields. The goal of precision agriculture is to develop technical solutions to optimize yields from inputs while conserving resources. Precision agriculture also encompasses new agricultural concepts such as vertical or urban agriculture, which are also based on scientific optimization of growth processes and disease and pest control.

Precision agriculture is based on four **main technology families** (source: Roland Berger)

- **Robotics and automation technology:**
Autonomous work is enabled by automated steering technology and high-precision positioning systems, as well as by integrated electronic communication systems.
- **Image processing and sensors:**
Data for assessing soil and crop health, etc. are collected via sensors, remote sensing systems, and geo-mapping.
- **Digitization and big data analytics:**
Data is analyzed to improve climate and soil forecasting, equipment performance optimization, and remote control in field monitoring.
- **Bioengineering:**
Seeds and chemicals are selected based on external conditions and seed development to improve resistance to specific agricultural and/or climatic conditions.

All four of these critical precision agriculture technology families are highly dependent on photonic technologies and solutions. Photonics contributes through:
Detection,
Monitoring,
Understanding, and
Control.
Photonics provides the most efficient tools for sensing, monitoring, control but also lighting, cleaning, sanitizing and boost the plant growth.

- **Photonic technologies and solutions:**
Robots require photonic sensors (cameras, lidars, etc.) to move autonomously, explore their environment, make decisions, and perform their tasks.
- **Imagery and sensors:**
Imaging is the recording of light, so all imaging is inherently photonic. Photonics is the only way to perform advanced analysis without contact. Most sensors for disease detection, soil and water analysis, crop and fruit quality, etc. are based on photonics.
- **Digitization and big data analytics:**
Fiber optics are the backbone of telecommunications networks. Transceivers, those components that convert light into electricity and vice versa, are critical to the performance of data centers.
- **Bioengineering:**
Bioengineering research relies heavily on microscopy techniques. Genetics would not be possible without PCR analysis read by photonic technologies.
Phenotyping is based on advanced imaging.
Almost all instruments used in science are based on photonics.


Photonics is a key enabler of EVERY precision farming application
Centimeter accuracy when driving and machining (GPS positioning, GNSS, LIDARS, etc.)
Collect and map data using sensors mounted on moving machines (moisture, nutrients, compaction, crop diseases)
Develop new varieties adapted to climate change, which require fewer inputs or are more productive.
Adapt and choose seeds/chemical inputs based on soil property analysis.
Adjust chemical inputs based on plant health and growth monitoring. Also adjust inputs with centimeter accuracy
Robotic weeding and pest control as an alternative to chemicals
Optimize lighting, reduce energy consumption
Reduce famer's workload through robotics and autonomous machining
Optimize productivity of greenhouses and vertical farming
Help decision making with handheld and low-cost sensors, equipment and/or smartphone apps
Minimize irrigation needs and water consumption
Share data and alerts with other agriculture stakeholders (neighboring farmers, cooperatives, banks, inputs, and seed suppliers etc.)
Evaluate crop quality, sort crop by quality standard, remove unwanted particles, etc.
Monitor livestock wellbeing
Optimize and monitor livestock growth
Provide accurate and local weather forecasts

The global market for photonics for precision agriculture is currently worth around 4.6 billion euros and is expected to virtually double by 2027 to a value of 9.1 billion euros. This corresponds to annual growth of around 15 percent.

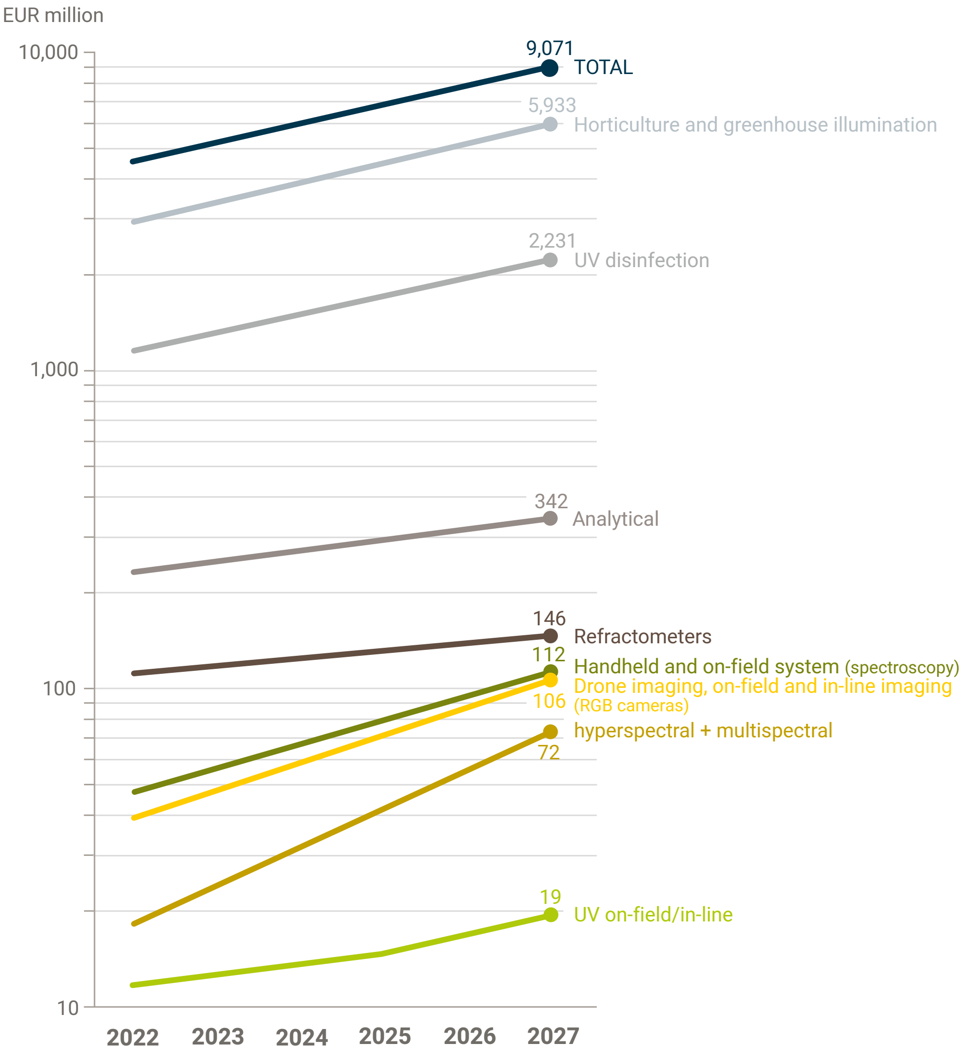
Lighting and UV disinfection still account for the largest share, but many other emerging technologies and fields of application have enormous potential.

Lighting includes greenhouse lighting and new types of agriculture such as vertical or urban farming. With the advent of LEDs, lighting a greenhouse is not only more energy efficient and saves a lot of CO_2 emissions, it is now also possible to adjust the wavelength of the lighting to provide exactly the light that the plants need and promote their growth.

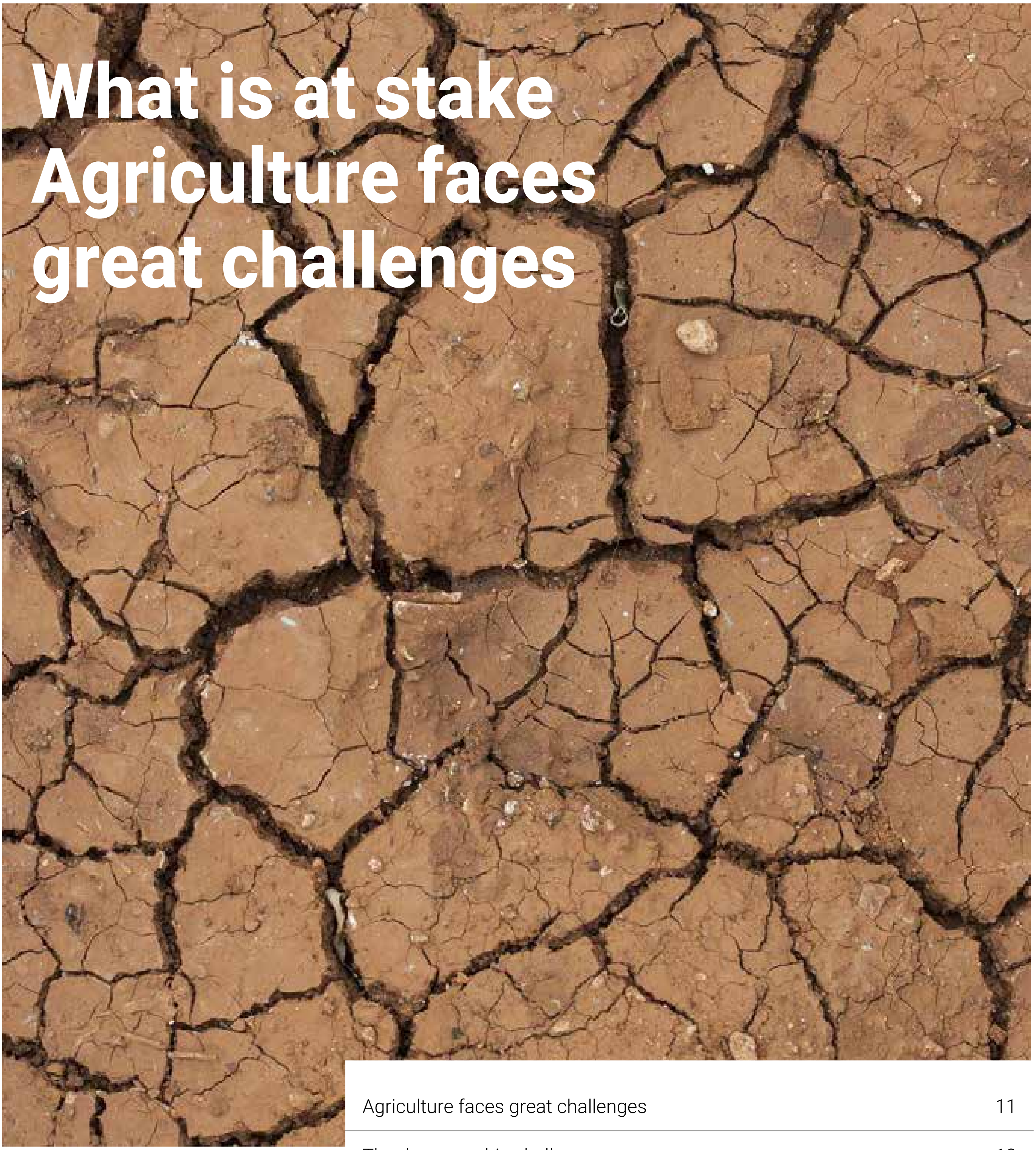
UV disinfection is currently the second largest market. Disinfected water is needed in agriculture, breeding, dairy production, nurseries, soil-less production, hydroponics/aeroponics, disinfection of drain backwaters, and reprocessing of nutrient solutions, or simply for irrigation. But UV can do even more: recent studies have shown that irradiating crops with UV-C boosts plant immunity and significantly reduces the need for chemicals to control pests and diseases. This is still a very young but promising market. Other opportunities for photonics in agriculture include imaging systems, either permanently installed or built into drones or robots, that can monitor crop growth, animal welfare and disease detection.

A more traditional but still important market is all instrumentation for monitoring, disease diagnosis, quality assessment and control, and sanitation testing. Equipment that was once only used in laboratories is becoming more miniaturized and can now be handheld or attached to tractors and machinery for precision agriculture in the field.

Global market forecast



What is at stake
Agriculture faces great challenges



Agriculture faces great challenges

Agriculture exploits of the wonders of nature to feed humans and domesticated animals. However, 11 percent of the world's population was undernourished in 2021, and the total number of people on the planet is expected to grow from 7.87 billion in 2021 to around 11 billion in 2100 – an increase of 40 percent (source: see page 12). It will not be possible to make additional land available to agriculture to match this population growth. As a result, feeding everyone will become a major challenge. The expansion of cities and urban areas is putting significant pressure on some regions, and deforestation is not an option as it threatens biodiversity and increases greenhouse gas emissions. But that is not all: while its yields have to increase dramatically, agriculture must also improve its practices: stop land degradation, preserve diversity, reduce pesticide use, reduce greenhouse gas emissions, and adapt to the effects of global warming.

In order to face these great challenges, agriculture needs to dramatically improve the governance and management of resources: land, water, ocean, fish, forests, etc. but also biodiversity, especially insects and birds which are vital for pollination. But these objectives will not be easy to achieve. A lot of scientific, economic, and social studies will be needed to improve current agricultural practices. And any recommendation as well as their implementation should take into account local farmers, their traditions, habits, social organization, ancestral knowledge of their own land, agricultural practices and investment capacity. In other words, the agriculture of the future will rely on science and technologies, as well as new and innovative approaches to farming, such as precision farming. But greater use of science-based methods and the adoption of more advanced technologies cannot be implemented unless farmers accept and play a part in these changes. Farmers are the most important stakeholders in the value chain, and extensive education and training programs will be necessary in order to allow farmers to be proactive partners join the agriculture revolution ahead.

The challenges ahead

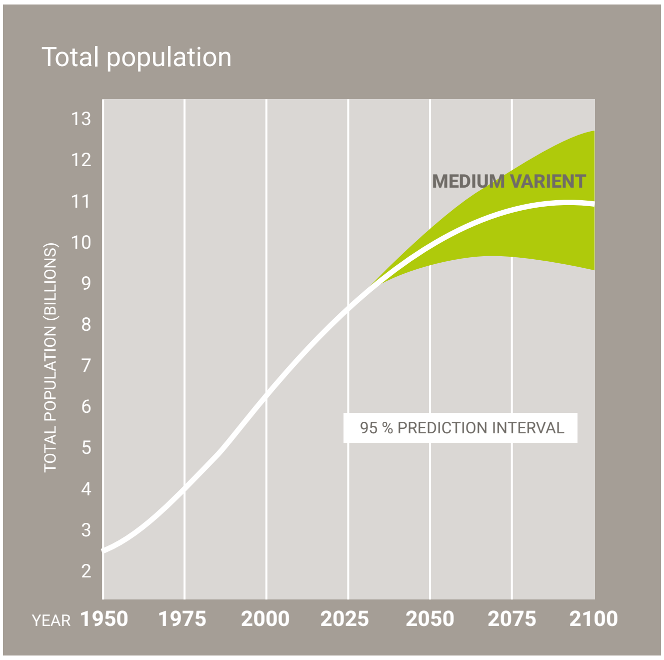
- Demographics / feeding the world
- End undernourishment and improve access to high quality food
- Stop land degradation
- Reduce pesticide use
- Reduce but also adapt to global warming impact
- Reduce GHG emissions

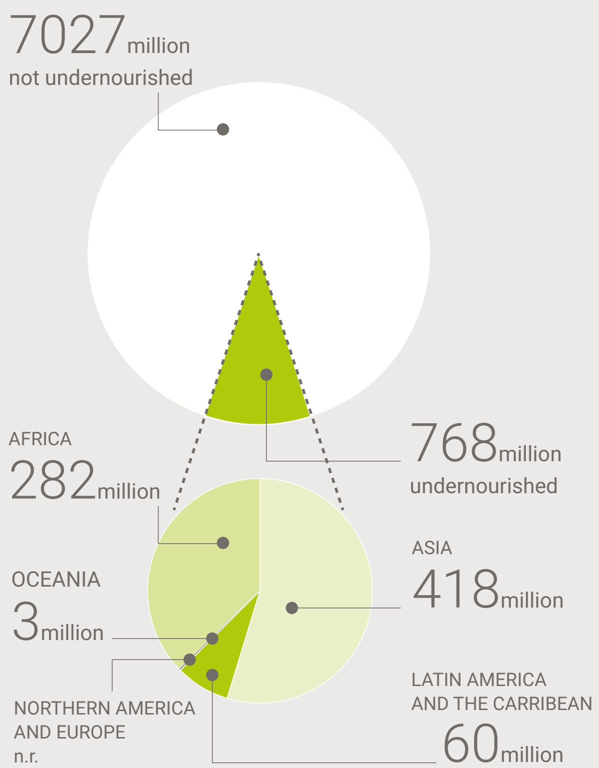
The solutions

- Conduct scientific, economic, and social studies to understand the challenges ahead and develop solutions
- **Develop new farming approaches and technologies that are**
  - Science-based
  - Respectful of traditions, habits, social organization, ancestral agricultural practices, and knowledge of local population
  - Compatible with farmers' investment capacity
- Support the adoption of new farming approaches and practices
- Train and educate farmers

WHAT IS AT STAKE

The demographic challenge





Notes: Number of undernourished in millions. Projected values based on the middle of the projected range.
n.r. = not reported, as the prevalence is less than 2.5 percent.
Source: FAO

- The world's population is expected to grow from 7.87 billion in 2021 to around 11 billion in 2100, i.e., an increase of 40%.
- In 2019, 11 percent of humankind were undernourished and 3 billion people were unable to afford a healthy diet.

United Nations, Department of Economic and Social Affairs, Population Division (2019). World Population Prospects 2019, Volume II: Demographic Profiles (ST/ESA/SER.A/427).FAO. 2021. La Situation mondiale de l'alimentation et de l'agriculture. Rendre les systèmes agroalimentaires plus résilients face aux chocs et aux situations de stress. Rome, FAO. https://doi.org/10.4060/cb4476fr

Pressure on land

- Agricultural land accounts for 36.9 percent of all land.
- Urban areas occupied less than 0.5 percent of the Earth's land surface in 2000. However, urban areas more than doubled in the period from 1992 to 2016 (+ 127 percent).
- The rapid growth of cities has had a significant impact on land and water resources, encroaching on good agricultural land, especially that used for horticulture.
- Some 33 percent of the worlds soil is moderately to highly degraded.
- Along with anthropogenic degradation, climate change is putting more pressure on agricultural land and leading to its deterioration.
- Soil erosion carries away 20 to 37 billion metric tons of topsoil annually, reducing crop yields and the soil's ability to store and distribute carbon, nutrients, and water. Annual cereal production losses due to erosion are estimated at 7.6 million tons.
- Globally, agriculture accounts for 72 percent of all surface and groundwater withdrawals, which are mainly for irrigation.

Land-degradation classes for global land cover, 2015

Land Cover	Total area (million ha)	Degradation (million ha)	Deterioration (million ha)	Stable (million ha)	Degraded (%)	Deteriorated (%)	Stable (%)
Cropland	1527	479	268	780	31	18	51
Rainfed	1212	340	212	660	28	17	54
Irrigated	315	139	57	120	44	18	38
Grassland	1910	246	642	1022	13	34	54
Trees	4335	485	1462	2388	11	34	55
Shrubs	1438	218	584	636	15	41	44
Herbs	203	16	51	136	8	25	67
Sparse vegetation	1034	85	499	450	8	48	44
Protected area	880	76	361	443	9	41	50

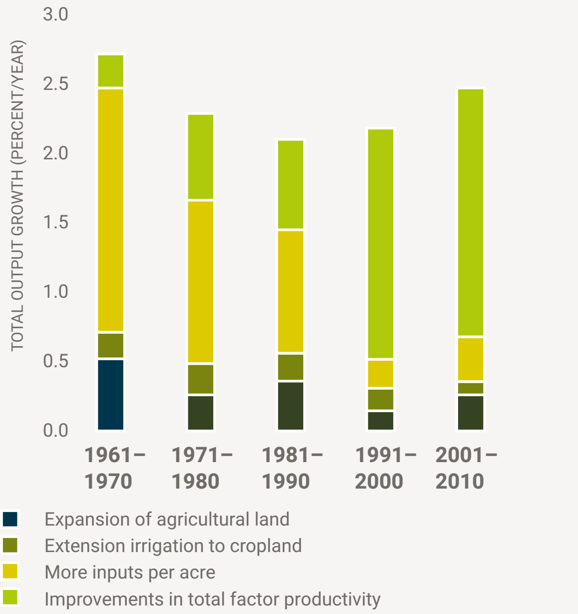
Note: The term degradation refers to high pressures from anthropogenic drivers.
All other declines in biophysical status are defined as deterioration.

FAO. 2021. The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Synthesis report 2021. Rome. https://doi.org/10.4060/cb7654en ingxu Huang et al 2020 Environ. Res. Lett. 15 084037, https://doi.org/10.1088/1748-9326/ab858c

The only way – produce more and better per hectare

- For a long time, agriculture was able to feed the world by cultivating more land and increasing inputs, fertilizers, and the use of pesticides.
- But it began to reach its limits in the 1980s. The addition of more and more inputs has now become less efficient and the resulting pollution caused by excess inputs in soil is giving cause for concern and becoming less acceptable.
- Since the 1990s, the only way to increase agriculture's productivity is to improve "total factor productivity", in other words, produce more and better per hectare:
  - Improve farming practices
  - Take in account the local soil and climate when choosing crop varieties
  - Monitor crop growth
  - Detect diseases and pests early
  - Optimize the use of inputs (e.g. fertilizer and water)
  - Invest in adapted machinery
  - etc.

Total output and factor productivity growth in world agriculture



Source: USDA 2021

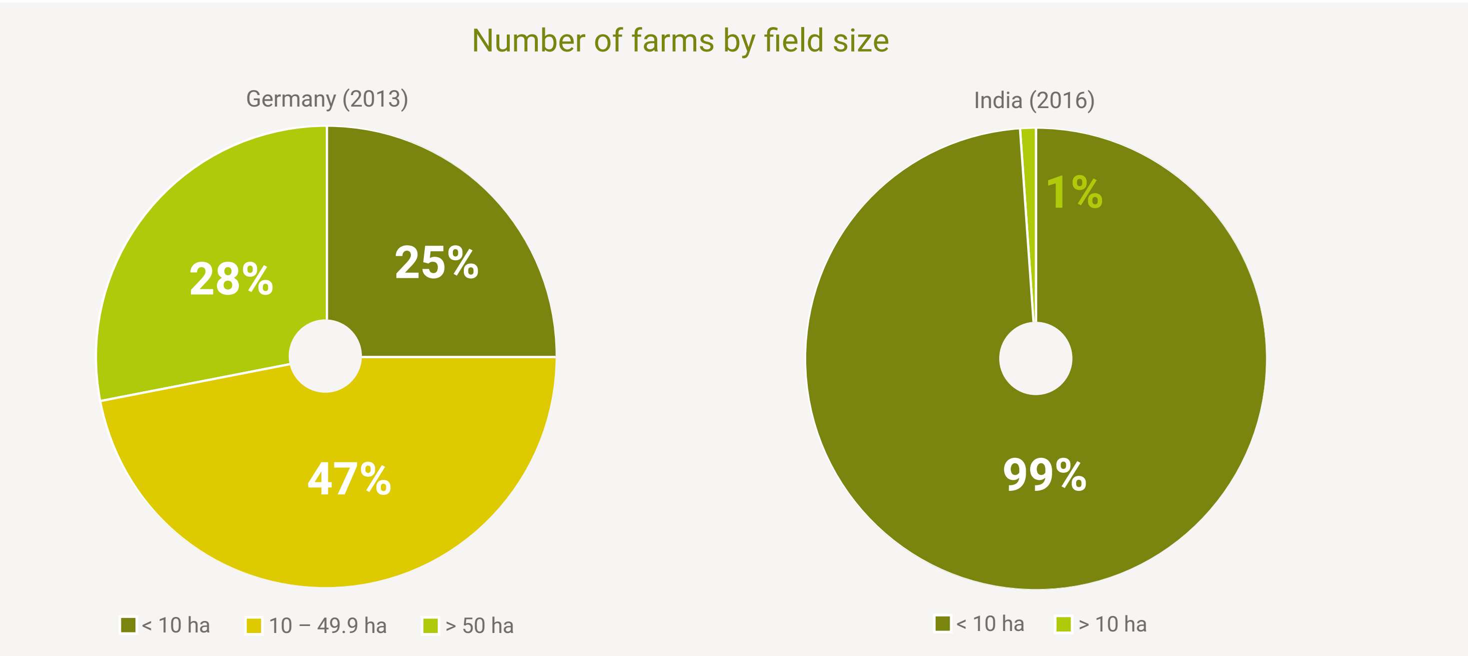
FAO. 2021. The State of the World's Land and Water Resources for Food and Agriculture – Systems at breaking point. Synthesis report 2021. Rome. https://doi.org/10.4060/cb7654en

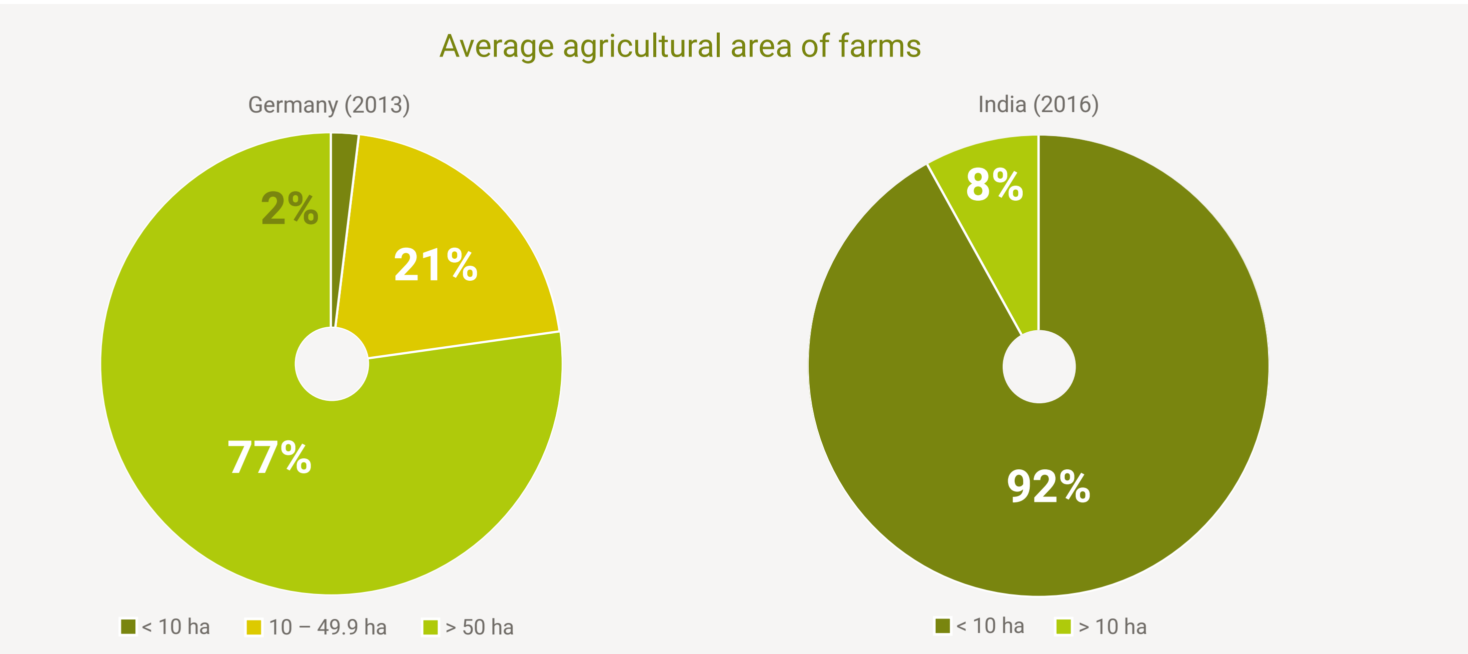
No evolution of farming without the full participation of farmers

- Farmers are the key stakeholders for better agriculture productivity. Their participation and acceptance are critical. They will not adopt new approaches unless they can expect an improvement in their conditions, i.e., better revenue, reduced effort, better resilience to climate hazards, etc.
- But all farmers are not the same. In high-income countries, farms are becoming larger and larger as the number of farmers is decreasing (see Germany profile below).

In other countries, especially in Asia, most farms are much smaller (see India below). Those countries, which contain the vast majority of the world's farmers, face the following huge challenges:

- Increasing the education level of farmers
- Providing them with accessible technologies that will improve their productivity significantly
- Supporting their financial and investment capacity.





Precision farming is an answer to the major challenges ahead

A need for new farming approaches that are more productive and sustainable

- A revolution in agriculture is ahead. New farming approaches and technologies are necessary to improve productivity and preserve land and biodiversity. They must be:
  - Science-based
  - Respectful of traditions, habits, social organization, ancestral agricultural practices, and knowledge of local population
  - Compatible with farmers' investment capacity.
- Precision agriculture is a farming management concept based on observing, measuring, and responding to inter- and intra-field variability in crops. The goal of precision agriculture is to build technical solutions with the goal of optimizing returns on inputs while preserving resources.
- Precision farming is well suited to large-scale production, but is not limited to it. In Asia, where the majority of farms are small, precision farming approaches will have to be adapted.
- Precision farming is compatible with organic approaches as they need to understand plant growth processes, diseases, and pest development from a scientific perspective and to evaluate the efficiency of organic practices.
- Precision farming also includes new farming concepts such as vertical or urban farming, which also rely on scientific optimization of growing processes and on disease and pest management.

Precision farming relies mainly on four technology families

The precision farming approach is valuable at every step of each agriculture production value chain. According to Roland Berger, the success of precision farming relies mainly on four technology families:

Robotics and automation technology:
Autonomous operations are enabled by automated steering technology and high-precision positioning systems as well as integrated electronic communication systems

Imagery and sensors:
Data for evaluation purposes of soil and crop health, etc. is collected via sensors, remote sensing systems, and geo-mapping

Digitization and big data analysis:
Data is analyzed in order to improve climate and soil predictions, performance optimization of equipment, as well as remote control in field monitoring

Bioengineering:
Seeds and chemicals are selected based on external conditions and evolution of seeds to enforce resistance to specific farm and/or climate conditions

And all these families could simply not exist without photonics!

Every step of the agriculture value chain can be improved by a precision farming approach

Strategic control points along a typical agricultural value chain (source: Roland Berger)

Input supply		Production	Post-harvest	Processing	Distribution/ marketing
Required machinery	Fleet distribution	Land preparation	Storage	Food processing	Commercialization
Preventive maintenance	Fleet rental	Planting	Transportation	Food packaging	Supply chain management
Remote diagnosis	Fleet management	Irrigation	Food pricing	Food transportation	Food marketing
Required seed	Input supply (e.g. fertilizer)	Fertilization	Food branding	Food traceability	Online shipping
Seed transformation	Soil analysis	Field monitoring	Commodity trading	Supply source management	
Climate prediction	Insurance (weather)	Harvesting	Insurance		
Data analytics (big data)	Remote sensing	Transportation	Infrastructure investment		
Satellite/drone mapping	Education/ training	Storage			

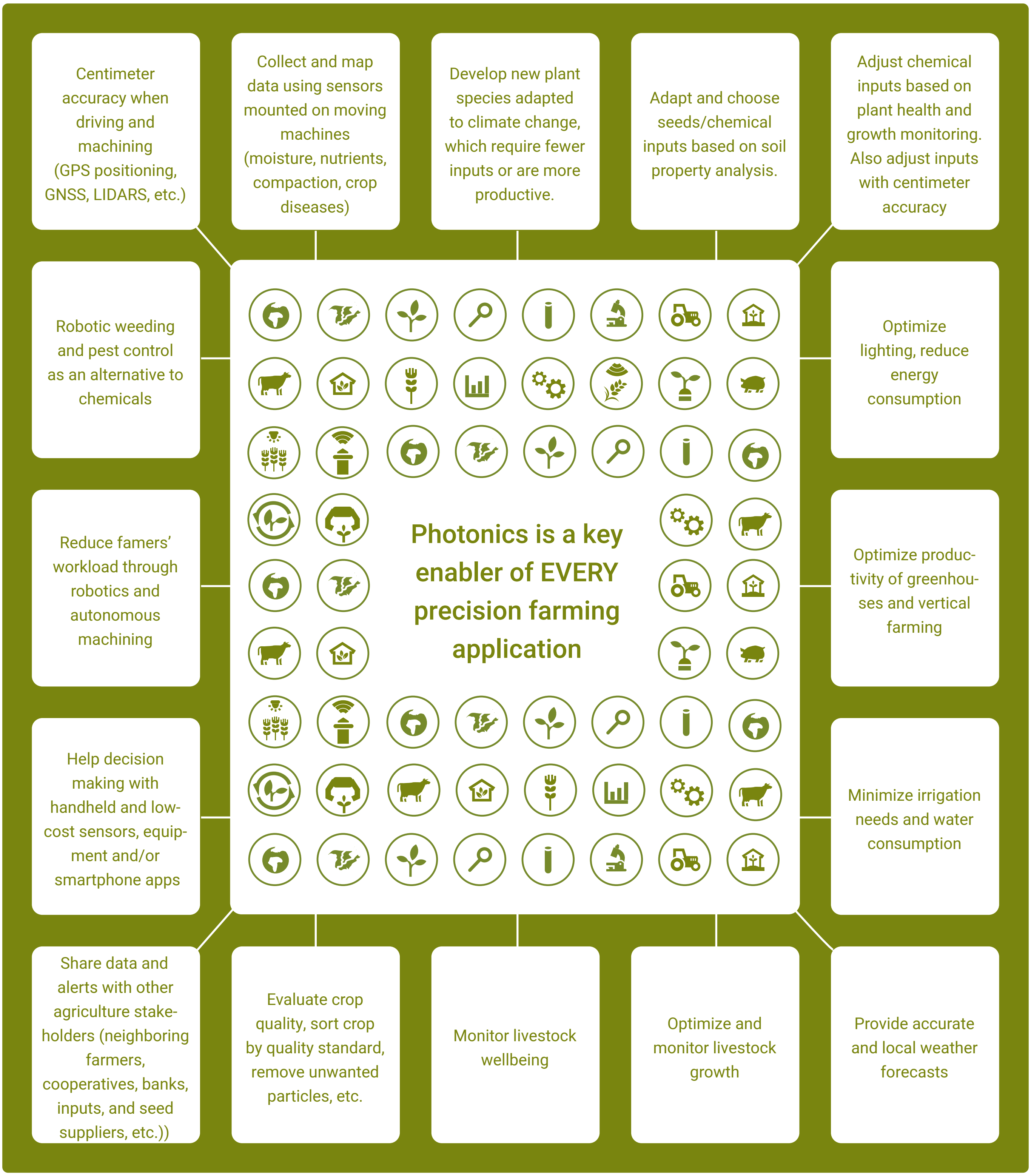
Not part of precision farming

End customers

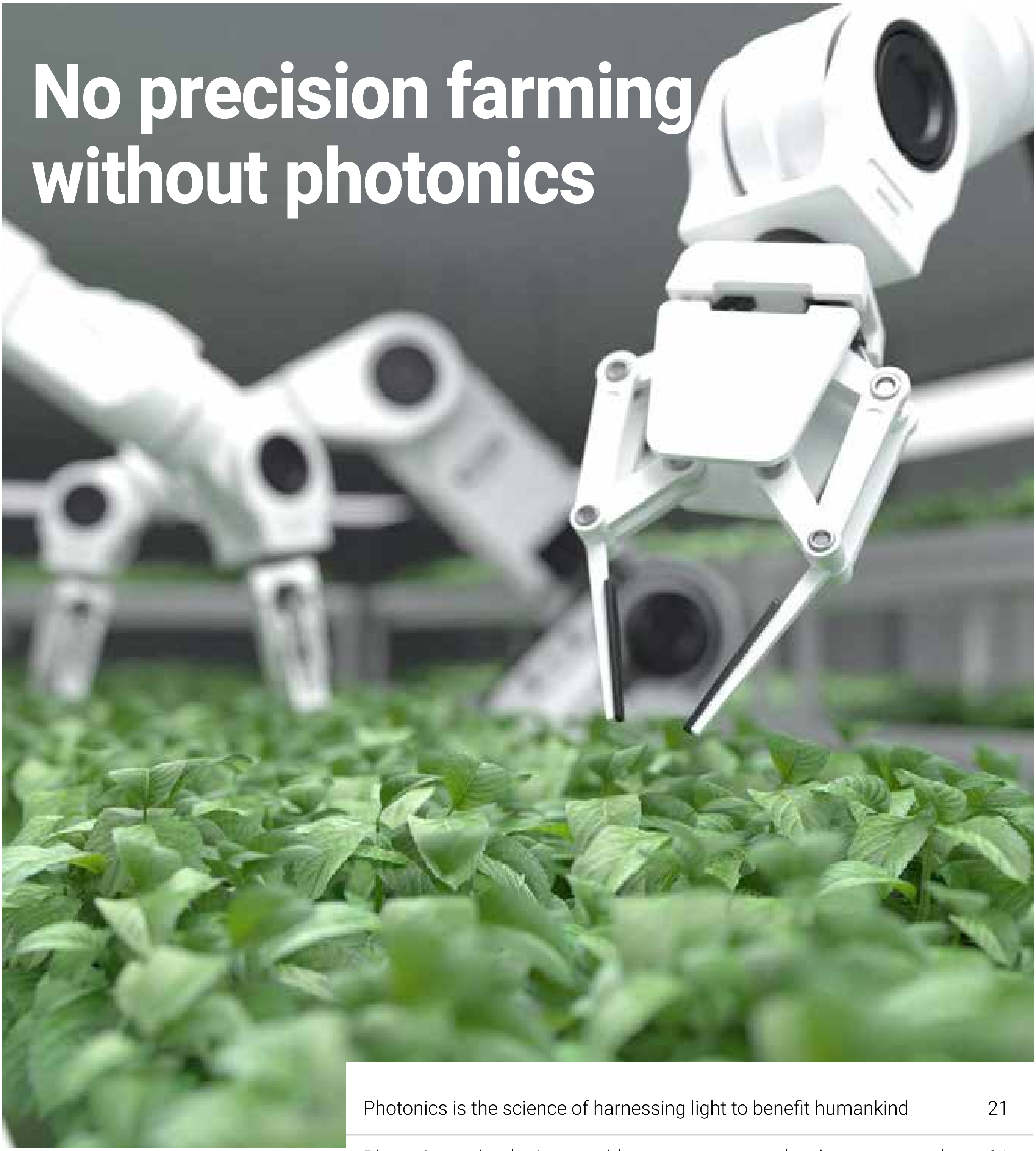
"Business opportunities in Precision Farming: will big data feed the world in the future?", Roland Berger Strategy Consultants GmbH, 2015

- Precision farming is not just about putting fancy sensors on a tractor.
- The precision farming approach is valuable at every step of each agriculture production value chain.

Selected applications of precision farming



No precision farming without photonics



Photonics is the science of harnessing light to benefit humankind

Photonics is the science of harnessing light to benefit humankind. Behind this definition lies a wide range of applications. Light is fast, precise, and clean – three unique properties that make photonics a critical technology when it comes to tackling the major challenges ahead.

All four critical technology families of precision farming are significantly dependent on photonic technologies and solutions:

- **Robotics and automation technology**
  Robots need photonic sensors (cameras, lidars, etc.) to move autonomously, explore their environment, make decisions, and perform their tasks.
- **Imaging and sensors:**
  Imaging is the recording of light, so all imaging is inherently photonic. Photonics is the only way to perform advanced analysis without contact. Most sensors for disease detection, soil and water analysis, crop and fruit quality, etc. are based on photonics.
- **Digitization and big data analysis:**
  Fiber optics are the backbone of telecommunications networks. Transceivers, those components that convert light into electricity and vice versa, are critical to the performance of data centers.
- **Bioengineering:**
  Bioengineering/Biotechnology research relies heavily on microscopy techniques. Genetics would not be possible without PCR analysis read by photonic technologies. Phenotyping is based on advanced imaging. Almost all instruments used in science are based on photonics.

Photonics technologies are able to measure complex data at any scale

Photonics technologies are able to measure complex data at any scale, from the atom to the entire planet.
They are a unique asset that help us understand and overcome the environmental challenges agriculture is facing.

Observation radius

PLANET	TERRITORY	FIELD	POINT-OF-USE	LABORATORY	ON CHIP OR AT LAB
1,000 km	**1–100** km	**1–1,000** m	**1–100** m	**0.1–100** cm	**10^3–100** μm
Atmosphere Wind Ocean Biosphere Meteorology Desertification Solar irradiation Climate change	Mapping Floods Wildfires Pollution Earthquakes Agriculture Urbanization Erosion/seashore	Agriculture Livestock Thermal efficiency Forestry Wildlife Erosion Subsoil Rivers	Agriculture Forestry Soil River water Potable water Waste management Thermal efficiency Air quality	Chemical analysis Soil, water analysis Pollution In vitro/in vivo diagnostics Fungi, bacteria, virus Pollen	Surface analysis Microscopy Advanced biological analysis In vitro diagnostics

Photonics technologies are able to measure complex data at any scale

- Today, agricultural innovation is very demanding because it is no longer possible to focus on the basic parameters used in the past, such as water, nitrates, and phosphates in soil, and local weather. All ecosystems must be taken into account.
- Erosion, local wind, insolation of fields, water availability, and local biodiversity need to be understood and preserved.
- The soil, which is made up of minerals, vegetal matter, animals, fungi, and bacteria, is a complex ecosystem by itself and also depends on its coverage (e.g., grass between fruit trees or vine stocks), the subsoil underneath, wind and water erosion, as well as a wide variety of natural inputs that sometimes come from very far away. Sand particles from the Sahara Desert travel all over the Mediterranean and regularly reach Paris. Even the soil of your garden is an interconnected ecosystem.
- As a consequence, other crops grown in fields are equally critical. If a pest or disease appears in one field, it will probably spread to other fields where the same crop is grown. Then the entire area must be monitored, not just the field in question.
- Weather alerts, climate change, and desertification processes are phenomena that must be monitored and studied on even wider scale.
- Photonics technologies are able to measure complex data at any scale, from the atom to the entire planet. They are a unique asset that help us understand and overcome the environmental challenges humankind is facing. At a global or local level, satellite and aerial imaging will be the only way to perform precise measurements over large areas.
- At field level, drone imaging, tractor-embedded photonic sensors, and miniaturized point-of-use instruments are becoming available and are being used increasingly by pioneers of precision agriculture.
- Last but not least, laboratory research is still a major tool for developing new approaches for agriculture. And almost every instrument used for research on biology, zoology, botanical science, agronomy, etc. are photonics-based, such as advanced microscopes and imaging cameras, spectrometers, or all fluorescence-based instruments.

Photonic technologies and solutions: Photonics is a key enabler of EVERY precision farming application

Advanced positioning

Cameras, LIDARS, 3D sensors …

Collect and map data

Imaging systems, cameras, spectrometers, spectral sensors

Develop new varieties

Microscopes, spectrometers, fluorescence detection, laboratory instrumentation

Adapt and choose seeds/chemical inputs based on soil property analysis.

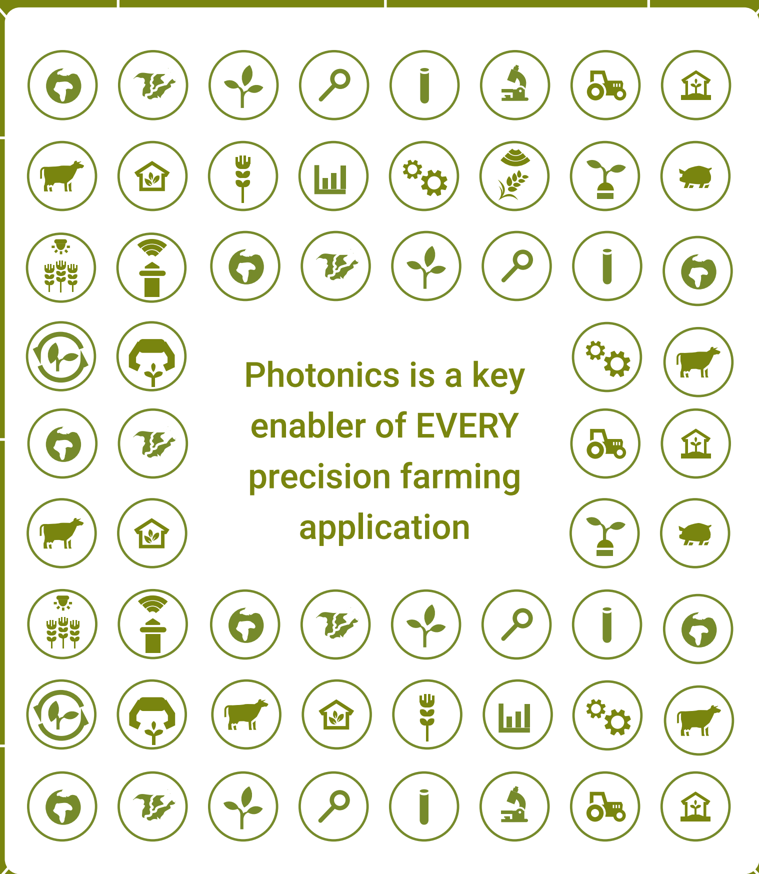
Microscopes, spectrometers, refractometers, fluorescence detection, instrumentation

Adjust chemical inputs with centimeter accuracy

Cameras, imaging systems, LIDARS, spectrometers, spectral sensors

Robotic weeding and pest control

Cameras, LIDARS, spectrometers, 3D sensors …



Optimize lighting, reduce energy consumption

Advanced lighting, spectral sensors

Robotics and autonomous machining

Cameras, LIDARS, spectrometers, 3D sensors …

Optimize productivity of greenhouses and vertical farming

Advanced lighting, imaging, cameras, spectroscopy, spectral sensing

Handheld and low-cost equipment

Refractometers, spectrometers, spectral sensing …

Minimize irrigation needs and water consumption

Imaging systems, cameras, UV lighting

Share data and alerts with other agriculture stakeholders

Fiber optics (telecom), transceivers (data centers) …

Evaluate crop quality, sort crop by quality standard, remove unwanted particles, etc.

Imaging systems, spectrometers, spectral sensors

Monitor livestock wellbeing

Imaging systems, spectrometers, spectral sensors

Optimize and monitor livestock growth

Imaging systems, spectrometers, spectral sensors

Provide accurate and local weather forecasts

Satellite imaging, LIDARS

Photonics is a key enabler of EVERY precision farming application

- The extreme versatility of photonic technologies and their efficiency at any scale make them a critical enabler of every precision farming application.
- In many of the precision activities described on the previous page, photonic technologies will measure and/or monitor the weather, plant growth, soil quality, the need for water or fertilizer, the appearance of a crop disease or pest, the well-being of animals, etc. However photonics can do much more.
- Before the science of harnessing light was known as photonics, greenhouses had been using solar light for a long time to collect heat and grow plants where and when it was too cold to do so in fields.
- Now, advanced lighting systems accelerate growth in greenhouses or vertical farming facilities even further thanks to optimized insulation of plants.
- 3D and LIDAR sensors, along with cameras, enable self-driving machines that interact with the crop with centimeter precision.
- UV sanitizing equipment cleans water obtained from greenhouses and recycles it for further watering.
- Other UV-based equipment sanitizes activated sludge and transforms it into fertilizer unless the sludge is use to produce biogas in processes monitored by photonic sensors.
- Recently, it was also demonstrated that UV flashes of certain crops, when applied at the right time, stimulate plant immunity and decrease significantly the need for pest control chemicals.
- Another contribution of precision farming is less visible. Precision farming generates high volumes of digital data which have to be transferred and shared through fiber-optic telecommunication networks, before being processed by computers and data centers. The photon and the electron are the twin particles of the digital world, and the challenge of precision farming is to digitalize agriculture to make it more efficient and sustainable.

Photonics is a critical enabler of precision farming

The following tables set out the photonic techniques which are regarded as critical enablers for more efficient and sustainable agriculture. But before being widely adopted in agriculture, photonics faces four major challenges that must be addressed with a realistic and humble approach:

1. A meeting of two worlds.

The photonics community shows great creativity when developing solutions, but photonics engineers are not farmers, and farmers and agronomists are not physicists. This means that in-depth consultation and a degree of translation are needed to understand the complexity of growing crops or livestock and translate this knowledge into appropriate photonics parameters.

2. Crops and livestock are incredibly diverse.

There are more than 10,000 varieties of apples, over 8,000 varieties of tomatoes, and more than 800 farmed races of cows! Each variety of crop or animal race has its specific shape, size, colour, physiology, disease, and pest. Each variety of crop or animal race has adapted to a specific climate and land. Each of them will produce or be suitable for a specific food. In other words, the challenge is not only to develop photonic sensors or equipment, but also to make these photonic sensors or equipment sufficiently versatile to be useful and efficient whatever the varieties used and by adjusting the operating parameters by software. This way, the same hardware can be used on a sufficiently large scale and be produced at an acceptable cost.

3. Easy to use is the key.

The third challenge is to develop advanced equipment that comprises high-tech components, but is easy to use by end-users with no physics background. This is a huge challenge since dealing with living matter means dealing with complexity. However, it is the responsibility of technology providers to tackle the difficulties.

4. Many farmers have a limited investment capacity.

It has been seen previously that there are huge farms which can afford to invest in innovative tools, but also a large number of small farms with much less revenue. Bigger farms are and will be the early adopters, not only because of their investment capacity but also because they usually have a better technical background. But in long term, all farms, even the small ones, should have access to more advanced technologies that will provide them with better revenue while respecting their traditions. Feeding the global population and addressing the sustainability challenges are at stake.

It will take time for these two worlds to come together. But there is no doubt that a bright future lies ahead as more and more photonics companies and start-ups enter the agriculture market. In addition to the interaction of these players with agriculture experts, artificial intelligence and deep learning will bring new ways to significantly accelerate the translation of agricultural requirements into physical parameters to be handled by photonics sensors and instruments.

Photonics is a critical enabler of precision farming

The table set out the photonics technologies available for enabling precision farming, but also throughout the value chain, from farm to fork.

Markets	Functions	Technologies
Agriculture & agro-equipment	■ Varietal innovation, adaptation of plants to climates and soils (phenotyping), plant protection, biocontrol ■ Systems and management of field crops and vines, including agricultural machinery / robotics ■ Remote sensing and spatial information systems	■ 3D laser scan, active and passive hyperspectral active and passive imaging, terahertz imaging and spectroscopy (hydration sensing), thermal imaging (evapotranspiration), NIR-MIR and Raman spectroscopy, high-resolution machine vision ■ CMOS and CCD cameras, NIR and UV handheld spectroscopy, multispectral and hyperspectral cameras, UV lighting, biosensors ■ VIS-NIR-SWIR-MIR imaging, SWIR sensors, high resolution satellite imaging, anemometer ■ UVC flashing for chemical reduction
Agriculture in green houses and off-field	■ Greenhouses, Vertical farm, Urban farms ■ At home greenhouse	■ LED lighting (UV-B and Vis), fiber-optic solar lighting, fiber-optic sensing, various spectroscopic devices, holographic and interferometric measurement (fish farms)
Breeding and aquaculture	■ Feed, additives, nutrition ■ Precision breeding ■ Diagnostic, veterinary drugs ■ Slaughterhouse ■ Fish farms	■ Spectroscopy (handheld, on-line) ■ CMOS cameras, high-speed cameras (biomechanics, Vision, Stereovision) ■ Biosensors (SPR, PIC) ■ 3D imaging, UV lighting, spectroscopy ■ Holographic and other interferometric devices
Food industry	■ At-line & On-line control ■ Rapid microbiology methods (detection, identification, characterization of particles below 10µm) ■ Detection of foreign bodies	■ Infrared spectroscopy (SWIR & MWIR), hyperspectral terahertz and Raman imaging, Cytometry, PIC, laser scanning, plenoptic imaging, Refractometers ■ Cytometry, plasmonic devices, spectroscopy (Raman, SPR), non-conventional imaging (holographic, speckle), PIC ■ Machine vision, X-rays, terahertz imaging
Retail	■ Presentation of food products at the point of sale (freshness, ripeness)	■ LED lighting, RGB imaging, hyperspectral and SWIR imaging ■ Embedded micro spectroscopy

Market figures and forecast

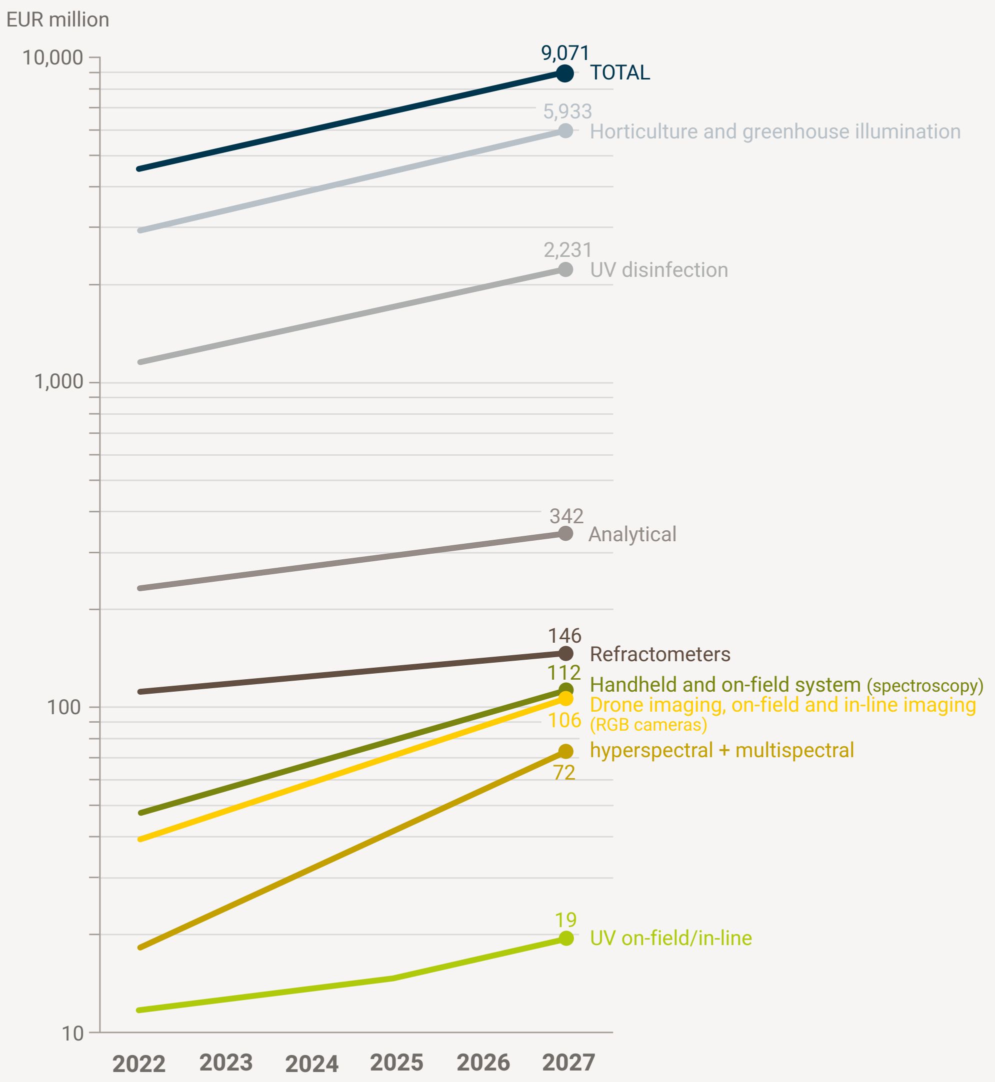
Market analysis and forecast

- The largest market for agricultural photonics is the illumination of greenhouses and new types of agriculture such as vertical or urban farming. With the advent of LEDs, lighting a greenhouse is not only more energy efficient and saves a lot of CO2 emissions, it is now also possible to adjust the wavelength of the lighting to provide exactly the light that the plants need and promote their growth.
- UV disinfection is the second largest market. Disinfected water is needed in agriculture, breeding, dairy production, nurseries, soil-less production, hydroponics/aeroponics, disinfection of drain backwaters, and reprocessing of nutrient solutions, or simply for irrigation. But UV can do even more: recent studies have shown that irradiating crops with UV-C boosts plant immunity and significantly reduces the need for chemicals to control pests and diseases. This is still a very young but promising market.
- Refractometers are also a significant and established market mainly dedicated to wine making and alcoholic beverage production for the control and prediction of alcohol through the measurement of sugar in the grape.
- Other opportunities for photonics in agriculture are imaging systems, which are fixed or embedded in drones or robots and can monitor the growth of crops, the well-being of animals, as well as detect diseases.
- A more traditional but still crucial market is all the instrumentation used for monitoring, disease diagnostics, quality assessment and control, as well as sanitary tests. Equipment that was previously used only in laboratories is becoming more and more miniaturized and can be now handheld or fitted onto tractors and machines in order to bring precision farming to the field.

Global market forecast (EUR million)

Family	Technology	2022	2023	2024	2025	2026	2027	CAGR (2022-2025)	CAGR (2026-2027)
UV processing	UV disinfection	1,158.9	1,321.2	1,506.2	1,717.0	1,957.4	2,231.5	14%	14%
	UV on-field/in-line	11.7	12.6	13.6	14.7	16.9	19.4	8%	15%
Imaging	hyperspectral + multispectral	18.2	24.0	31.7	41.9	55.3	72.9	32%	32%
	Drone imaging, on-field and in-line imaging (RGB cameras)	39.3	47.9	58.5	71.4	87.0	106.2	22%	22%
Measurement & spectroscopy	Refractometers	111.5	117.8	124.4	131.3	138.7	146.4	6%	6%
	Analytical	233.3	251.9	272.1	293.9	317.4	342.8	8%	8%
	Handheld and on-field systems (spectroscopy)	47.2	56.1	66.8	79.5	94.6	112.6	19%	19%
	Other	52.9	60.8	70.0	80.5	92.5	106.4	15%	15%
Illumination	Horticulture and greenhouse illumination	2,950.0	3,392.5	3,901.4	4,486.6	5,159.6	5,933.5	15%	15%
Total		**4,623.0**	**5,284.9**	**6,044.6**	**6,916.7**	**7,919.4**	**9,071.7**	**14%**	**15%**

Global market forecast



Market expectations

Lighting and disinfection markets: improve the ROI. In the biggest and more established lighting and UV disinfection markets, expectations are associated with efficiency, energy saving, reliability and maintainability for a better return on investment.

- In the lighting segment, adjusting the illumination spectra as well as the illumination cycles and personalizing them to each specific crop are expected to boost growth while saving energy. LED lighting enables this fine-tuning, but engineers need recommendations from agronomists in order to know what is best for each plant throughout its growing cycle.

Analytical and emerging markets: save time, reduce uncertainty and make life simpler. Farming is a very complex activity. You have to cope with the complexity of living material and ecosystems: crops or the animals being bred, soil, weather, water, diseases and pests. Success in farming depends on care and know-how. But today, above and beyond these ancestral difficulties, farmers have to deal with many more constraints and risks: traceability, safety, regulations, administrative and paper work, finance, markets price volatility, availability and price of inputs, pressure on prices by the agrofood and retail sector, and now demands and requirements regarding the environment and climate. Any innovation entering the agriculture market should propose a solution that will address some of these problems.

Challenges of farms

Detect risks at an early stage: Weather, water, diseases, pests... Monitoring the evolution of the risk when it has occurred, recommending remedial actions, etc.

Save time and increase productivity. Automating repetitive and time-consuming tasks and reducing effort.

Bring flexibility. Many farmers grow several crops in order to diversify their revenue and maintain the soil quality of their land. They may also change the crop species or variety to adapt to the climate or the market demand. Photonic tools are a profitable investment, but also a significant one. This is why these tools have to be versatile enough. This means using the same hardware platform as much as possible and adapting it through software.

Optimize the use of inputs. Save money, protect the environment, and be more sustainable.

Facilitate traceability. Guarantee safety and quality for all stakeholders, reduce administrative work.

Estimate the quality grade of the crop. Give an early estimate of the selling price, anticipate the revenue, detect fraud and unfair competition.

Build standardized solutions, especially regarding farming data. Farmers use their farming data for many purposes: farming optimization, sanitary control, negotiations with their clients, administrative declarations, insurance and bank loan negotiations... They need to control their data and be free to choose their tools.

Outlook

- However, the use of AI and deep learning might accelerate the growth of the market:
  - Deep learning is very suitable for dealing with complex problems such as growing crops, where you have to take so many parameters into account (water, weather, soil, inputs, diseases and pests, etc.) and do not have all the equations for simulating all the ecosystem interactions.
  - Rather than requiring a full scientific understanding of the optimum growth parameters of a crop, the training for deep learning approaches is quicker and requires less effort. It will then be easier and less costly to adapt a system to a specific crop, animal race, or just a local context.
- As a consequence, the combination of versatile hardware and AI-based software might be a good strategy to develop photonics-based products that could be less costly to manufacture, thanks to bigger scales, and less costly to personalize to each specific need, thanks to a deep learning approach.
- For the coming years, bigger farms are and will be the early adopters, not only because of their investment capacity but also because they usually have a better technical background. However, in the long term, all farms, even the smallest ones, should have access to more advanced technologies that will provide them with better revenue while respecting their traditions. And it is probable that the way to spread their use will be to develop simple but efficient portable tools, such as refractometers in wine making, or to create professional mobile applications that will exploit very low-cost integrated sensors (spectral sensors, cameras…) embedded in consumer devices such as smartphones.

Landscape

Global inventory of companies

The following tables show a list of photonics companies that claim to be active in the agriculture markets. Most of the companies listed are developing hardware, either photonics components or photonics-based solutions or systems.

Some only provide software dedicated to the processing of data obtained through photonics. The list is focused on photonics technologies. Companies providing general software for farm management are not listed, or if they are listed it is because they also develop photonics technologies (such as sensors).

Refractometer manufacturers are provided in a separate list. Only handheld and portable digital refractometers are shown.

Component manufacturers:
Many photonics-based systems used in agriculture embed generic photonics components such as cameras, hyperspectral cameras, sensors, LIDARs, spectrometers, etc. that can be used for other applications. But this inventory is based on corporate internet communication. Only components manufacturers which clearly claim their activity in the agriculture market are listed even it is mostly probable that some others sell components to agriculture systems integrators.

Agriculture photonics component and solution companies

Name	Activity	Country
EVK DI Kerschhaggl GmbH	Food sorting	Austria
Winsen	Livestock: temperature, humidity, ammonia, CO2, H2S	China
Photon Systems Instruments	Plant and algae phenotyping	Czech Republic
Delaval	Dairy : Cell count, health	Denmark
Foss Analytical A/S	Food and agricultural analysis	Denmark
GrainSense	Measuring grain quality	Finland
GrainSense Oy	Sensors	Finland
Led Tailor INNOVA7ION	UV disinfection	Finland
Lumichip Light	Lighting and disinfection	Finland
Lumichip Oy	Lighting and disinfection	Finland
Metrohm Nordic Oy	Sensing and instrumentation	Finland
Specim	Spectral imaging	Finland
Specim, Spectral Imaging Oy Ltd	Hyperspectral imaging	Finland
Spectral Engines	Smart farming	Finland
Spectral Engines Oy	Spectroscopy	Finland
Valoya	LED grow lights	Finland
Valoya Oy	Lighting and disinfection	Finland
A2 Photonics Sensors	Spray analyser	France
Abiotec	UV disinfection	France
Amarok Biotechnologies	Analysis services	France
CARBON BEE	Real-time weed detection	France
Cascade	Wavelength conversion technologies	France
Cimtech	Engineering	France
Copeeks	Livestock: CO_2, NH_3, humidity, animal behavior	France
Force-A ripening assessment	Optimal harvest, early disease detection	France
FRUITION SCIENCES	Wine making	France
GEOMATIC DEVELOPMENT	Aerial imaging services	France
GreenHouse Keeper	Greenhouse sensing, imaging and lighting	France
Green Shield Technology	Vineyard imaging and laser weed suppression	France
GREENTROPISM	Data processing for precision farming	France
Hiphen	Drone imaging for phenotyping	France
IKK	Sensing and instrumentation	France
INS. FRANCAIS VIGNE ET DU VIN	Research services	France
MAF AGROBOTIC	Integrator : plant and fruit sorting	France
NEW VISION TECHNOLOGIES	Imaging solutions	France
OPTOMACHINES	Analytics imaging	France
OPTOMESURES	Analytics and temperature control	France

Name	Activity	Country
PARROT	Drone imaging	France
Photon Lines	Early disease detection, ripeness assessment	France
SANODEV	Disinfection	France
SPECTRALYS INNOVATION	Food quality analytics	France
YELLOW SCAN	Forestry: LIDAR analytics	France
Carl Zeiss Spectroscopy GmbH	Precision Farming Solution for Agriculture and Food	Germany
CP Control in applied Physiology	Sensors for monitoring fruit development in the field and in storage	Germany
Crocus Labs UG	Lighting	Germany
Deka Sensor + Technologie	Temperature, light sensors	Germany
FarmFacts GmbH/Next Farming	On-field crop sensor	Germany
Fritzmeier	Crop management	Germany
Geophilus GbR	Sensing, soil mapping	Germany
Hydrometeorologische Instrumente und Messanlagen	Sensing	Germany
LemnaTec (Nynomic AG)	Phenotyping, imaging, image analysis, machine learning, crop health	Germany
LOMAGRI GmbH	Equipment	Germany
m-u-t GmbH (Nynomic AG)	Photonics for tailor-made customer solutions	Germany
Narva - G.L.E.	Lighting	Germany
OSRAM AG	Lighting	Germany
Pronova Analysentechnik GmbH & Co. KG	Sensing and instrumentation	Germany
Robert Bosch GmbH	Smart spraying	Germany
Stenon GmbH	Laboratory-independent, real-time soil analysis	Germany
tec5 AG (Nynomic AG)	Spectroscopy & optical sensing	Germany
Trinamix	Spectroscopy	Germany
VISTA GmbH	Satellite imaging processing	Germany
Agriot	Computer Vision for Real-Time Analysis of Nutrient Content	Israel
Agroscout	Computer vision & Optimal harvest	Israel
Agrowing	Spectral imaging sensor	Israel
Bioled	Advanced lighting for crops	Israel
Clarifruit	Computer vision for fruit growth optimization	Israel
Dot soil	Soil Nitrate spectroscopic sensor	Israel
Fermata	Computer vision & Optimal harvest fro greenhouses	Israel
FFRobotics	Imaging and robotics for fruit harvesting	Israel
Fruitspec	Computer vision for fruit growth optimization	Israel

Name	Activity	Country
Go smart	Submarine camera for fishery optimization	Israel
Metomotion	Ripeness assessment, optimal harvest	Israel
Taranis	Computer vision & Optimal harvest	Israel
Alitec	R&D services	Italy
ARIESPACE SRL	Satellite imaging processing	Italy
CDR Srl	Quality and ripeness analysis	Italy
Ecobioservices srl	Instrumentation	Italy
FEDI IMPIANTI sas di Matteini Marco & C.	PV equipment	Italy
FOTOSINTETICA & MICROBIOLOGICA	Photobioreactors	Italy
Iptsat	Satellite imaging processing	Italy
Mate srl	Laboratory	Italy
MEEO Srl	Satellite imaging processing	Italy
Microgeo srl	On-field imaging systems	Italy
Netsens s.r.l.	Wireless sensors	Italy
Planetek Italia srl	Satellite and aerial imaging processing	Italy
Protec s.r.l.	Optical sorting	Italy
Hamamatsu Photonics (Deutschland GmbH)	UV-VIS imaging used in food inspection	Japan
Panasonic Corporation	Optimal harvest	Japan
Adviesbureau JFH Snel	Sensors and services	Netherlands
Aris	Phenotyping	Netherlands
Avantes B.V.	Spectroscopy	Netherlands
Bird Control Group	Laser bird control	Netherlands
Cosine Group B.V.	Instrumentation and sensing	Netherlands
De Greef's Wagen-, Carrosserie- en Machinebouw B.V.	Sorting solutions	Netherlands
EMS	Gas, temperature, climate, humidity	Netherlands
Euromex Microscopen BV	Microscopy	Netherlands
Fancom	Particles, optical, distance	Netherlands
Kipp & Zonen BV	iInstrumentation and sensing	Netherlands
LioniX international	Photonic gas sensors	Netherlands
Ocean Optics BV	Spectroscopy	Netherlands
perClass BV	Hyperspectral imaging data analysis	Netherlands
PRIVA	Photometers for weather and photosynthesis	Netherlands
Sensor Partners BV	Sensors	Netherlands
Sensor Sense B.V.	Gas sensing	Netherlands
Teledyne DALSA B.V.	Imaging	Netherlands
Van Remmen UV Techniek B.V.	UV disinfection	Netherlands
WPS	Sorting and phenotyping	Netherlands
Yara International	Crop fertilization	Norway

Name	Activity	Country
Sunforest	Portable non-destructive quality meter	South Korea
Agilent Technologies	Food safety testing	Spain
Agrobot	Integrator, optimal harvest	Spain
BCB Informática y Control	Livestock imaging	Spain
DELAIR	Drone imaging	Spain
Laserfood	Vegetables and fruit laser marking	Spain
Agilent Technologies Sweden AB	Food safety testing	Sweden
Agricam	Temperature, bacteria, thermal, BHB ketones	Sweden
Agricam AB	Sensing for livestock farming	Sweden
BoMill	Grain sorting	Sweden
BoMill AB	Grain sorting	Sweden
Heliospectra	LED grow lights	Sweden
Heliospectra AB (publ)	Advanced lighting for crops	Sweden
Leica geosystems	Localisation and data management	Sweden
Luda Farm	Security, motion detection	Sweden
Prediktera AB	Hyperspectral imaging	Sweden
Senseair AB	Gas sensing	Sweden
Trimble AB	Sensors and integrated solutions	Sweden
WoodEye AB	Wood imaging	Sweden
CAMPDEN BRI	Analysis solution	United Kingdom
Dräger	Ammonia	United Kingdom
Halma plc	UV disinfection	United Kingdom
Heraeus Noblelight America LLC	UV and IR illumination for air purification	United Kingdom
Labman Automation Ltd	Lab instrumentation	United Kingdom
Sensoren Dogtooth Technologies	Integrator / optimal harvest	United Kingdom
Turnock Limited	Lighting	United Kingdom
Abundant Robotics	Optimal harvest	USA
Deere & Company	Early disease detection	USA
Energid Technologies Corp.	Optimal harvest	USA
FaunaPhotonics	Early disease detection	USA
Felix Instruments - F750 Produce	Quality meter	USA
Harvest Croo	Optimal harvest	USA
Headwall Photonics Inc.	Crop health / hyperspectral	USA
Iron Ox	Optimal harvest	USA
PepsoCo	Early disease detection	USA
Raven Industries	Guidance for autonomous equipment	USA
Root AI	Ripeness assessment, optimal harvest	USA
TurfScout	Sensors & services	USA
Violet Defense	UV light treatment	USA
Vision Robotics Corp.	Optimal harvest	USA

Handheld and digital refractometer manufacturers

Refractometers	Country
Biobase Meihua Trading Co., Ltd.	China
Bonajay (Shenzhen) Technology Co., Ltd.	China
Hangzhou Lohand Biological Co.,Ltd.	China
Mesu Lab Instruments (Guangzhou) Co., Ltd.	China
Shanghai Jingke Scientific Instrument Co., Ltd.	China
Shengzhou Hongyuan Refractometer Manufacturing Co., Ltd.	China
Shenzhen Welllbom Technology Co., Ltd.	China
Shenzhen Yago Technology Limited	China
A.KRÜSS Optronic GmbH	Germany
ARCARDA GmbH	Germany
ARIANA Industrie GmbH	Germany
KERN & SOHN GmbH	Germany
PCE Instruments	Germany
Pronova	Germany
ACMAS	India
ADVANCE RESEARCH INSTRUMENTS COMPANY	India
Bionics Scientific	India
Labline Stock Centre	India
NATIONAL ANALYTICAL CORPORATION	India
Yatherm	India
Optika Srl	Italy
ACE SANGYOKIKI INC.	Japan

Refractometers	Country
Atago	Japan
KYOTO ELECTRONICS MANUFACTURING CO., LTD	Japan
FJDynamics Pte.Ltd	Singapore
Three In One Enterprises Co., Ltd.	Taiwan
Bellingham + Stanley	United Kingdom
Index Instrument ltd	United Kingdom
AFAB Enterprises	USA
AFAB Enterprises	USA
Agtec	USA
Cole-Parmer	USA
DeltaTRAK, Inc.	USA
Extech (FLIR)	USA
Hanna Instruments	USA
Mettler-Toledo	USA
Milwaukee	USA
MISCO REFRACTOMETER	USA
Reed Instrument	USA
Reichert (Ametek)	USA
Spectrum Technologies, Inc.	USA
Sper Scientific	USA
Vee Gee Scientific	USA

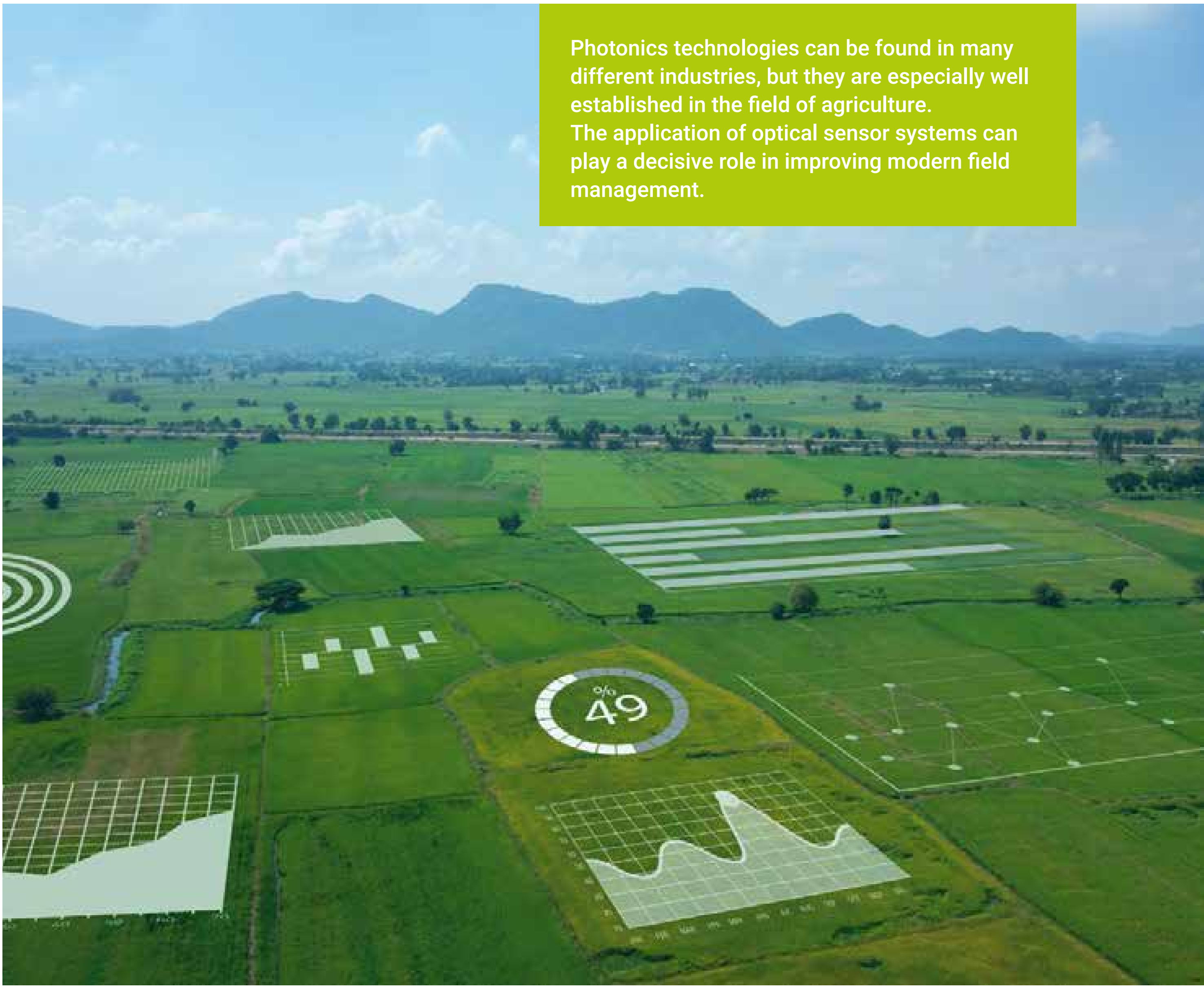
The German landscape

- Germany is well represented in three major market segments: lighting for greenhouses, indoor farming and refractometers and optical sensors.
- In lighting, Narva - G.L.E. specializes in traditional metal halide lamps and high-pressure sodium lamps, while OSRAM and Crocus Labs focus on LED technologies.
- Handheld and digital refractometers are used to determine the must or sugar content in the fruit and wine-making industries. They help predict the future alcohol content of wine. They can also be used to determine the degree of ripening for fruits such as tomatoes, melons, or kiwis or the water and sugar content in honey. In this very competitive market where China and India are very active, and where the US is dominant, German companies are in the top four (A.KRÜSS Optronic GmbH, ARCARDA GmbH, ARIANA Industrie GmbH, KERN & SOHN GmbH, PCE Instruments, Pronova).
- Other German companies provide multiple types of sensors, mainly spectral sensors. The products and services of the Nynomic Group (m-u-t, tec5, LemnaTec) are based on a wide range of intelligent sensors for measuring optical radiation and smart technologies for data acquisition, processing, and evaluation. ZEISS, in extensive developments and field tests in the past with one of the leading agricultural machinery manufacturer, has succeeded in developing an NIR sensor for the agricultural machinery market.
- Some companies (Isaria, Farmfacts…) not only provide components, but also develop full farming management systems which include photonic sensors.
- Vista GmbH provides remote sensing and modeling for hydrology, agriculture and the environment based on satellite imaging.

Source : https://isaria-digitalfarming.com/en/

Developing measurement technology in the farming sector is a matter of teamwork

We put four questions on the subject of "Photonics Technologies for Agriculture" to Maik Müller and Fabian Peters, Executive Directors of the Nynomic Group



Photonics technologies can be found in many different industries, but they are especially well established in the field of agriculture. The application of optical sensor systems can play a decisive role in improving modern field management.

Maik Müller *Fabian Peters*
Executive Directors of Nynomic AG

Are applications in the agricultural sector already established in the photonics industry?

Maik Müller: Of course. Optical methods are already very well established and widely used in this area, from breeding and seed production to sowing, growing, and finally during harvesting. For example, photonics technologies have been used to assess the quality of fruits and soil for some time now. They have also become a standard way of rating plants and monitoring yields. In soil analysis, they help determine nutrient requirements or serve to monitor legally stipulated threshold values for the total nitrogen content. And a very exciting topic is the more recent development of optical methods for a more targeted and therefore a more sustainable application of herbicides or fertilizers.

From the perspective of the measuring device manufacturer, how does the agricultural industry differ from other industries?

Maik Müller: Agribusiness has clearly been playing a pioneering role in the implementation of process analytical technology. Here, new optical measurement concepts, comprising purpose-built sensors mounted directly on machinery, have brought online analysis straight to the point of action.
This eliminated the need for laboratory analyses and the associated time lag. Furthermore, combining the wide variety of analysis data with additional information, such as GPS coordinates, has enabled innovative field and process management. In doing so, the agricultural sector was one of the first to consistently implement the digitalization trend in industry.

What is the reason for this high pressure for innovation in the agricultural sector?

Fabian Peters: Earnings from these technical innovations in a price-sensitive and cost-driven sector such as the agricultural industry are immediately noticeable. First, the direct availability of automated analysis results on site within fractions of a second allows populations and crops to be immediately captured, classified, and sorted automatically using agricultural machinery. This offers enormous potential to dramatically reduce operating costs and infrastructure. And even more importantly, the technology makes a significant contribution to optimizing yields and thus to ensuring profitability. Another example is the selective use of fertilizers and herbicides, the amount of which is controlled by optical sensors, thus significantly reducing the necessary consumption of these products. This is not only beneficial to the environment, but is also a cost-saving measure. All of this means that modern, economical, and ecological agriculture is no longer conceivable without the implementation of smart sensor concepts, which relate to trends such as precision farming.

And how do you meet those challenges in your organizations?

Fabian Peters: One thing we recognized at an early stage within the Nynomic Group is that the successful developing measurement technology in the farming sector is a matter of teamwork. In our group, innovative ideas and solutions emerge from the interaction of the various specialized companies, and range from components development and system integration to highly application-oriented implementation. Close cooperation with numerous external partners in this field is also extremely valuable. The resulting synergy of machinery and sensor expertise leads to seamlessly integrated on-board system solutions. In addition, this opens the door to advanced measurement technology for in-house applications such as breeding, as well as to research or portable devices.

NYNOMIC
THE PHOTONICS GROUP

Nynomic AG is an internationally leading manufacturer of products for permanent, non-contact, and non-destructive optical measurement technology. The products and services of the Nynomic Group are based on a wide range of intelligent sensors for measuring optical radiation and smart technologies for data acquisition, processing, and evaluation.

Nynomic – The Photonics Group
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The role of optical sensing in soil quality evaluation

Optical sensors can be used to generate spatially resolved quality maps of the soil quickly and easily, enabling the right nutrient decisi-ons to be taken. In this way, crop yield and quality are maximized by selecting the right fertilizer and applying the correct amount of nu-trients at the right time and in the right place.

A purpose-built and robust NIR on-board manure sensor makes slurry application not only easier, but also more intelligent. This technology allows the generation of soil maps for the visualization of geo-tagged yield potential and for the docu-mentation of nitrogen replenishment to comply with legal requirements.

Soil quality by its very nature makes a substantial contribution to the successful cultivation of crops and hence to the highest possible yield. Optimal results are obtained by regularly analyzing both chemical composition and nutrient content.

Optical sensors for simple and fast measurements in the field are available, thus eliminating the need for time-consuming and costly sampling for wet chemical analysis.

At its most basic, handheld sensors for field use provide full analytical data in a matter of seconds. In addition, vehicle- or drone-based sensors are capable of fully covering areas of agricultural land, delivering spatially resolved maps of soil quality. In contrast to sampling-based methods, it is only through the use of optical methods that significantly more effective and efficient field management becomes possible.

The approach for optical sensors is nearly always the same: Light reflected from the ground – either natural light from the sun or from artificial light sources– is collected by sensors in the UV, VIS, or NIR range and analyzed in spectral terms.

In this application, an NIR sensor is directly mounted to the slurry tank, measuring nutrient concentrations of organic fertilizer. Based on these results, it is possible to apply the exact amount of fertilizer the crop really needs. Ingredients such as nitrogen, ammonium nitrogen, potassium, phosphorus, and dry matter can be reliably captured for unrivaled precision in fertilization.

From these measurements, it is possible to determine the chemical composition of the soil. This in turn is a prerequisite for the subsequent cultivation or preparation of the soil. For example, the application of fertilizer has to be controlled precisely, which also happens by means of optical sensor technology. However, the amount of fertilizer applied is not the only decisive factor for optimized plant growth. Environmental aspects also make it necessary to avoid soil overload by spreading too much fertilizer and to comply with legally stipulated limits (total nitrogen).

Modern fertilizer vehicles are therefore frequently fitted with optical sensors that analyze the usually quite inhomogeneous liquid or dry fertilizers for their relevant ingredients. The data collected is used to adjust the spread rate automatically via control valves to ensure the correct amount of nutrients is always applied to the area in question.

Efficient control and monitoring of the fertilization process with optical sensors mounted directly on top of an agricultural machine. The soil on both sides of the machine is scanned, and soil quality data is provided in real-time to the on-board system. Plants are only fertilized when necessary to reduce the environmental impact to a minimum.

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Harvesting machines – tough demands on optical sensors

Today, optical sensors allow immediate result testing in real-time during harvest. Making sensitive measuring technology available under difficult conditions, such as during harvesting, is the real challenge for manufacturers of measuring devices.

An NIR sensor directly mounted on an agricultural machine is shown in operation. The use of this technology allows the identification of dry matter as well as starch, sugar, and many other quality criteria, depending on the respective crop.

Monitoring and documentation of both yield and harvest quality are the most important factors for measuring the success of agricultural applications. In addition to the retrospective evaluation of measures, this is the basis for optimizing, future processes. For this purpose, optical sensor devices are directly mounted on harvesting machines such as grain forage harvesters and beet harvesters. Here, the crop material passes the sensor and is analyzed while the machine is in operation. Material-specific absorption bands, usually in the near-infrared range, are used as a basis and are recorded spectrally. From this measurement data, the sensor is able to calculate the concentration of relevant ingredients and thus determine the changing chemical composition of the crop flow in real time. For example, dry matter can directly be determined from the water or moisture content. Combining this measurement data with the respective GPS position of the harvester leads to maps of the respective crop areas ("geo-tagging"), in which the yield is shown with precision down to the meter and with spatial resolution. Besides dry matter, many other crop quality parameters can also be recorded, such as protein, starch, or sugar content. Since the acceptance, utilization, and, in particular, price of agricultural products are often defined according to quality, a sensor-based classification and, if necessary, sorting of the harvested goods directly in the field is highly efficient. Determination of quality criteria also has an important role to play in the field of plant breeding, as they are linked to key breeding objectives, such as optimizing the protein content of energy maize. In field trials, new varieties are fully analyzed while they are still being harvested and directly on the machine, thanks to optical sensors that are used after test cultivation. This eliminates the need for steps such as sampling and further processing in analytical laboratories. Using optical sensors on harvesting machines puts tough demands on manufacturers of measuring equipment: In addition to the harsh environmental conditions including dirt, moisture, and vibrations, the systems have to operate extremely reliably and be highly available. The time slots for harvests are quite short and not repeatable, which means that there is no room for a system failure. It is therefore imperative that users can fully rely on those devices, which are essential for their crop management.

User-friendliness is another key aspect. The sensor systems are designed in such a way as to carry out automated measuring routines without any major user interaction and, if necessary, to transmit the analysis results to the harvester 's onboard system in real time. This data can then be used to generate further commands for machine control and to create consistent documentation.

For use on a variety of agricultural machines, fully automated NIR sensors are available for measuring liquid and solid substances in reflection. Different applications are possible, for example on a liquid manure tanker or on a combine harvester. The changeover is carried out in a few swift moves.

The sensor systems are directly connected to the on-board network via bus systems, allowing automated classification and, if required, direct sorting of the harvested fruit based on the measurement data. In addition, detailed maps are created from the geo-tagged data for improved field management following the concept of precision farming.

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Plant growth assessment using optical measurement technologies

Frequent plant growth monitoring using optical sensors is now a common practice in the agricultural industry. This not only offers economic benefits, but also makes a substantial contribution to protecting the environment.

Greenhouse plants can be monitored using optical sensing techniques at different levels of mechanization, starting with basic ceiling-mounted cameras. A more advanced approach is the use of hyperspectral cameras for phenotyping of plants in greenhouses, growth rooms, or indoor farms.

Photonic measurement techniques are ideal for monitoring plant growth, as they are completely non-destructive and make sure that many parameters that are important for evaluating the condition of individual plants can be identified by measuring their optical properties. This procedure takes advantage of the fact that the plant components and ingredients each absorb very different proportions of light.

In typical measurement setups, light gets reflected from the plant and is detected and analyzed by a measuring device in the visible UV or infrared range. This data can then be used to calculate concentrations of chemical constituents, based on which a reliable and comprehensive phenotypic assessment can be made. Scanning or direct imaging measurement cameras can even be used to visualize distributions within plants.

Users of this technique include plant growers who need to evaluate new varieties for germination characteristics as well as or shoot growth in the different growth phases according to the respective breeding objectives. The characterization of the many thousands of new experimental plants each year is hardly imaginable without the possibilities of modern high-throughput sensor technology.

A semi-automated phenotyping system for laboratory samples that enables measurements to be made using a range of optical sensors including hyperspectral cameras, chlorophyll fluorescence cameras, RGB cameras or laser scanners. The system's automatic camera exchange system provides high flexibility and can handle up to five cameras at once. The software package enables phenotypic information to be derived from all sensor recordings. Applications comprise structural and physiological phenotyping of seeds and seedlings, young plants, detached plant parts, and more. Samples can be displayed in small pots and trays, petri dishes, multi-well plates, or germination trays.

Phenotyping is the quantitative recording of plant appearance. Environmental influences or the effects of plant diseases are identified using optical methods. For this purpose, leaf discs grown in multi-well plates are analyzed using dedicated camera systems. Hundreds of plantlets can thus be analyzed in short time windows, and it is possible to tell from the external appearance of the young plants whether they have the desired characteristics.

Moreover, regular monitoring of plant growth is now also generally established in agriculture. Optical sensors mounted on vehicles or drones can be used to completely record entire inventories, which can be used, for example, to determine nutrient requirements with spatial resolution. In addition, plant diseases or a possible pest infestation can be detected at an early stage. Based on the sensor data, appropriate localized measures can then be taken, resulting in more targeted action on the one hand and less use of chemical pesticides on the other. These aspects are vital in terms of both business management and environmental protection.

In addition to monitoring crop health, another reason for using photonic measurement techniques is to detect and localize weeds in the vicinity of crops. Optical sensor systems make it possible to use herbicides for modern field management in a targeted manner and therefore only where they are required.

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Application Area: Agriculture, Industrial, and Photonics

Photonics Technologies for Agriculture

Professionals in agriculture and food packaging industries know exactly how important it is to analyze, monitor, and inspect food products in the packaging process. Fortunately, many solutions that address this are available using today's technologies including SWIR, InGaAs, and CCD/CMOS.

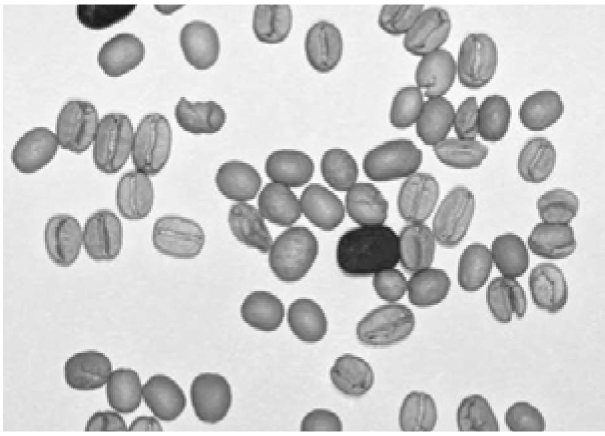
Description in layman's terms of the scope

Cameras and sensors are integrated into devices designed for improving food inspection, sorting, safety, and quality. These systems can identify issues in food products and packaging before they are shipped out. Vision inspection can prevent unsafe, low-quality food from reaching shelves and save businesses costs on returned defective packages.

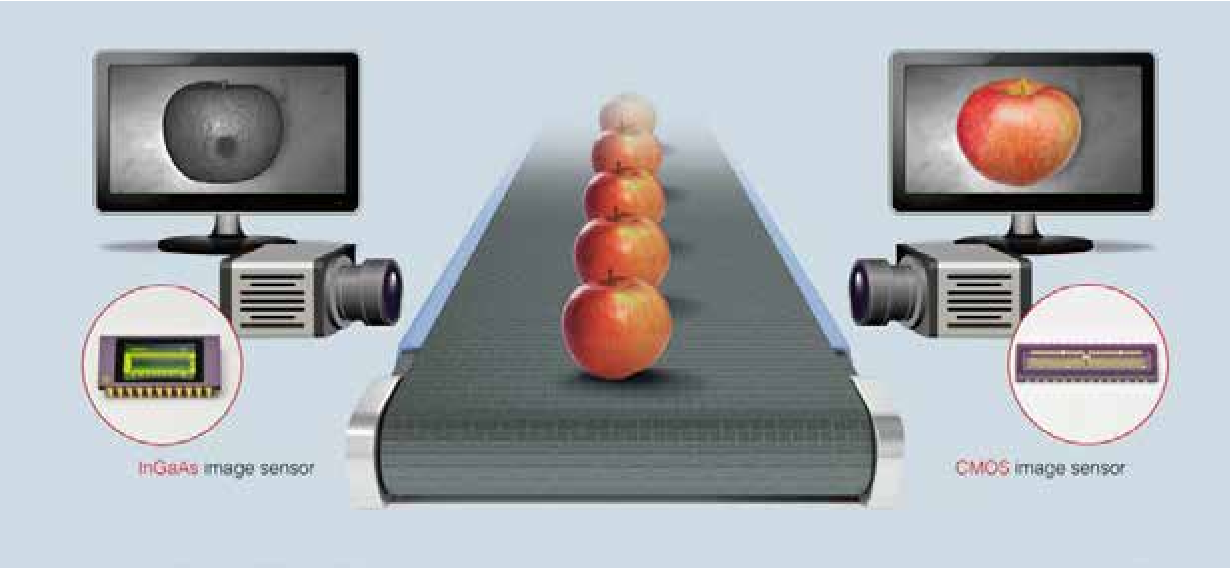
One example can be seen in coffee production, which is enhanced through machine vision. Coffee beans are placed on the tarp on the ground for drying, then raked up and put in a hopper. During the raking process, rocks or gravel can easily get mixed in with the coffee beans. These stones need to be sorted out before the beans are packaged.

If stones go unnoticed and are packaged with the coffee beans, they can lead to health issues and can cause coffee grinders to break. Machine vision can be used to distinguish between items of similar shape and size. Placing cameras and detectors in strategic locations throughout the line will help identify materials based on their SWIR spectra, enabling distinction between coffee beans and stones.Moisture content can greatly affect the quality and shelf life of agricultural products. The slight trace of additional moisture can indicate the start of mold. A bruise indicates that oxygen has penetrated the skin or peel and gotten into the fruit. Bruised fruit or vegetables will have brown spots and/or eventually turn completely brown. While most are safe to eat, bruised fruit is not aesthetically appealing or can be over-ripe.

Visible images of rocks & coffee beans, difficult to detect the difference.



C12741–03 InGaAs camera, clearly identifies rocks



For example when apples travel down the conveyor belt, they are scanned using InGaAs and CMOS cameras. The InGaAs camera will show defects beginning to form under the skin that a human eye cannot see. The CMOS camera will show visible defects.

To optimize the food sorting inspection process, different high-speed imaging devices should be placed at strategic locations on the conveyor belt. These sensors will automatically scan produce, detecting visible and invisible defects on produce that should be filtered out, so they do not reach the store.

Description of the concrete sustainability effect

With the world population currently at 7.7 billion and expected to grow to 9.7 billion by 2025, agricultural companies are faced with the challenge of keeping up with the increasing demand for high-quality food. They must continually optimize the food sorting and inspection process.

Unfortunately, human vision is unreliable as it can confuse similar-looking colors and cannot identify defects under food skin or packaging. However, machine vision can reduce errors in food sorting and packaging by detecting issues a human being would not be able to see. For example, noticing moisture content on or beneath the skin of food, capturing leaky packaging, and distinguishing between foreign objects and goods of similar shapes and colors.

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Brief technological description of the process/product

For UV-VIS imaging used in food inspection, Hamamatsu Photonics offers a broad selection of CMOS image sensors in linear and area arrays. CMOS linear image sensors with high sensitivity from UV to the near-infrared region up to 1,100 nm are available in a variety of pixel configurations (from 128 pixels to 4,096 pixels), sensitivity, and line speeds. CMOS area image sensors are available in various configurations, ranging from 30 x 30 pixels to 1,280 x 1,024 pixels. InGaAs linear image sensors are suitable for in-line sorting of agricultural products because of their high-speed line rate and high sensitivity. They are available in a variety of cutoff wavelengths, pixel counts, and line readout speeds. InGaAs area image sensors are suitable for hyperspectral imaging. High-speed frame rate, low readout noise and high sensitivity characterize these area arrays. They are available in various cutoff wavelengths, pixel arrays, and frame rates. InGaAs cameras provide plug-and-play solutions using 1D or 2D InGaAs image sensors. They are also an easy solution for multispectral/ hyperspectral imaging (HSI) cameras to be built based on the original camera. SWIR hyperspectral imaging is just beginning for food processing applications such as almond grading and quality inspection, capable not only of detecting foreign objects but also of grading food such as nuts or identifying ingredients. Hamamatsu Photonics provides a complete product line with various cutoff wavelengths from 1.7 µm to 2.5 µm, also providing options from sensors to modules. Compact MOEMS spectrometers like InGaAs TF Series and SMD Spectrometer, covering the spectral range from UV to NIR with integrated optical system, image sensor and driver circuit.

An optimal use of resources with non-destructive near-infrared spectroscopy

The challenge

The world's population is growing, and with it the price and scarcity of resources such as fertilizers. This means that yields in agriculture need to increase. At the same time, farmers must comply with fertilizer regulations and use resources in an environmentally friendly way. Modern near-infrared (NIR) sensor technology can be used on agricultural machines such as forage and combine harvesters as well as slurry tankers to help conserve resources and use them in a targeted way.

NIR sensor from ZEISS mounted on a harvesting machine

NIR sensors can continuously analyze crops when mounted directly at the spout on forage harvesters

The moisture values of chopped corn are determined in real time and used to control the chopping length. This ensures that lactic acid is produced by the corn silage in storage and means that perfectly adjusted feed is guaranteed. On top of that, the measured protein and starch values can also be used to create yield maps.

Yet one major challenge is integrating high-precision measurement technology on agricultural machinery under extremely harsh environmental conditions. Sensors must deliver consistently high levels of measurement performance across extremely variable climates – from European winters to Australian summers. They also need to have a high IP classification against dust and moisture and be resistant to the strong vibrations and shocks on harvesting machines.

Working together with one of the leading agricultural machinery manufacturer, ZEISS Spectroscopy has undertaken comprehensive development work and field tests to create an NIR sensor for agricultural machinery. It provides outstanding measurement performance, a failure rate of less than 1% and a service life greater than seven years in field use. The sensor is marketed as an OEM product. The next generation of the ZEISS sensor will be available from 2024 with extensive improvements.

The technology

Near-infrared spectroscopy is a non-destructive analysis method that is both highly accurate and precise. It works in the 800 to 2,500 nanometer wavelength range, putting it between the visible spectral (VIS) and mid-infrared (IR) range. Light in this wavelength causes molecules to vibrate in a very specific way.

If samples are exposed to a broadband light source, the reflected light contains spectral information that can be used like a fingerprint to identify the substances contained within. By correlating this information with laboratory analysis of samples, it is possible to create a model that can then easily and immediately determine a predictive value from spectral analysis, such as the protein content of maize, for example. This enables automated, real-time control and is already used in various production processes, such as agriculture and food manufacturing.

In the future, modern AI methods such as deep learning will further improve the accuracy and reliability of this type of analytics.

How it works

Linking GPS data from the harvesting machine with the nutrient values obtained by analyzing the harvested crops provides an objective, two-dimensional representation of the yield across the field. These spatially resolved yield maps are collected and evaluated over several years and are used to optimize recurring agricultural processes such as field fertilization. A needs-based application of fertilizer based on the yield maps and the nutrient target values for nitrogen (N), phosphorus (P) and potassium (K) in kg/ha makes it possible to reduce the use of resources and groundwater pollution.

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Mobile spectroscopy is now a reality

Integrating spectroscopic measurement into agricultural machinery is an effective way to control production and optimize the use of resources. However, oftentimes it's also necessary to obtain data in the field or at production facilities by taking samples directly from crops, raw bulk goods or finished products. In areas like renewable energy, it's important to analyze biomass and good data about quality parameters such as moisture, protein, starch, fat content, ADF and NDF makes it possible to create and optimize feed for livestock, for example.

That's where handheld, mobile NIR spectrometers are exceptionally useful. These small, mobile devices can be used by just about anyone to gather data that allows for the optimization of production processes and the monitoring of raw materials. They have the same levels of performance as full-sized spectrometers and can provide precise, lab-quality results just about anywhere and under almost any environmental conditions. Products such as AURA® handheld NIR from ZEISS give farmers, food producers and processors high levels of flexibility when they need fast and accurate results, especially since the optical core is the same as the sensor integrated to vehicles and calibration models are aligned with both devices.

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AURA® handheld NIR offers laboratory spectrometer quality on the move

ISARIA (Fritzmeier Umwelttechnik Group)

ISARIA is a subsidiary of the Fritzmeier Umwelttechnik Group. The company commercializes intelligent crop management systems based on spectral plant sensors to be embedded in tractors for the optimization of nitrogen fertilization. The technology can be used for many crops, like cereals, corn, rape, potatoes, or grassland.

The ISARIA system calculates two plant indices:

- The biomass index provides information about crop density
- The N-supply index is a measure of the current nitrogen supply to the crop

These two indices are used to calculate the correct quantity of fertiliser for the current crop automatically, depending on the selected fertiliser strategy.

ISARIA system has two versions:

- A passive option which uses the solar light reflected on plants
- An active version using intense LEDs for illuminating the crops and making the system independent of weather conditions and daylight

Source: https://isaria-digitalfarming.com/en/

FarmFacts GmbH – Next Farming

NEXT Farming is a trading name of FarmFacts GmbH. The company provides a full farming management system based on software, mobile apps, and a range of sensors and equipment including:

- Weather Station
- Embedded active photonics sensors
- Imaging field monitoring systems
- Drone surveillance and pest control.

The company also commercializes services and software for the exploitation of satellite remote sensing data and images.

Source : https://www.nextfarming.com/farmer

Stenon

Founded in 2018 in Potsdam, Germany, Stenon commercializes an on-field soil analysis system based on a multi-sensor (including spectroscopy) device and a data processing environment using machine learning.

This product is said to replace laboratory analysis, making it faster and more efficient. The company claims that farmers use data to make decisions about cultivation, boosting yield, crop quality, and soil health, while saving significant amounts of time and money by not needing to use a soil testing laboratory.

The Stenon technology is patented, certified, and in use in 20 countries.

https://stenon.io/en/

Pronova Analysentechnik GmbH & Co. KG

PRONOVA was founded in 1998 and is based on the activities and know-how of AEG in the area of gas analysis, which was exclusively taken over by PRONOVA. PRONOVA is certified in accordance with DIN/ISO 9001 2008. Following the acquisition of iRAS® Automation GmbH (Bad Klosterlausnitz) in 2004, the water analysis technology segment was added. PRONOVA's STELZNER® products have been providing solutions for agricultural measurement systems since 2006.

PRONOVA's main goal is to provide professional, application-specific process-control solutions for various smaller applications in gas and fluid analysis.

Refractometers for wine, honey, fruit juices, and alcohol
Refractometers are optical instruments for measuring dissolved materials in water-based solutions. Their functionality is based on the principle of varying optical refraction in liquids: light travels through a liquid and the angle of refraction is measured against a scale. This indicates the quantity of dissolved solids in the liquid.

Refractometers are used to determine the must or sugar content in the fruit and wine-making industries. They can also be used to determine the degree of ripening of fruits such as tomatoes, melons, or kiwis, or the water and sugar content in honey.

AMOLA® for photometric determination of NPK
The AMOLA® Agrar Mobile Lab contains all the key reagents, equipment, and accessories to make an assessment in the lab or in the field. It can be used to determine any of the main readily soluble, plant-available nutrients: nitrogen, phosphorus, and potassium (NPK). It is useful for agriculture, horticulture, tree nurseries, and composting plants applications.

Ammonium can be specified as NH4 and NH4-N; nitrate can be specified as NO3 and NO3-N. The total nitrogen is determined from the sum of the ammonium- and nitrate-nitrogen (NH4-N + NO3-N). Phosphate is calculated as PO4, PO4-P, or P2O5, and potassium is calculated as K or K2O.

Source: https://pronova.de

Crocus Labs GmbH

Crocus Labs™ GmbH is based in Berlin, Germany. They develop luminaires optimized to boost plant growth in indoor farming facilities:

- Greenhouses
- Indoor farms
- Vertical farms
- Growth Chambers

Example of crops that can be grown with their system:

- Strawberries
- Tomatoes
- Leafy greens
- Microgreens
- Cannabis
- Peppers

Crocus Labs claims that its solution can provide high yield all the year round, while keeping the electricity costs and CAPEX low. The solution is based on a combination of three specific technologies:

- A novel LED technology has very high efficacy across the photosynthetically active radiation spectrum.
- Miniaturized sensor systems and advanced data analytics, which provide precise lighting control.
- A self-learning system able to continuously improve growth recipes to produce quality yield while further reducing the power requirements of the luminaires.

https://crocuslabs.com
Radetsky, L. C. (2018). LED and HID horticultural luminaire testing report. Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY.

Useful definitions and glossary

GPS	Global Positioning System
GNSS	Global Navigation Satellite System
Photosynthetically active radiation (PAR)	Photosynthetically active radiation (PAR) designates the spectral range (wave band) of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.
Total factor productivity (TFP)	TFP measures the amount of agricultural output produced from the combined set of land, labor, capital, and material resources employed in farm production.
LIDAR	Light Detection And Ranging, LIDARs are like RADARs except they use light instead of radio to detect objects.
Hyperspectral imaging	Hyperspectral imaging collects and processes information from across the electromagnetic spectrum. The goal of hyperspectral imaging is to obtain the spectrum for each pixel in the image of a scene, with the purpose of finding objects, identifying materials, or detecting processes.
Phenotyping	Assessment of complex plant traits such as growth, development, tolerance, resistance, architecture, physiology, ecology, yield, and the basic measurement of individual quantitative parameters that form the basis for complex trait assessment (Li et al. 2014). Modern plant phenotyping, often using non-invasive technologies and digital technologies, is an emerging science and provides essential information on how genetics, epigenetics, environmental pressures, and crop management (farming) can guide selection toward productive plants suitable for their environment.
Refractometer	A refractometer is a laboratory or field device for the measurement of an index of refraction (refractometry). The index of refraction is calculated from the observed refraction angle using Snell's law. In agriculture, the index of refraction can be used to determine the concentration of sugar in grape juice or wine, for example.
Spectrometer	A spectrometer is a scientific instrument used to separate and measure spectral components of a physical phenomenon. Spectrometer is a broad term often used to describe instruments that measure a continuous variable of a phenomenon where the spectral components are somehow mixed.

Messe München GmbH
LASER World of PHOTONICS 2023

The global trade show and leading platform for the laser and photonics industry

LASER World of PHOTONICS is the world's leading trade fair for the laser and photonics industry. It covers the entire market – from optoelectronics and laser manufacturing to imaging, sensors, and biophotonics. World of QUANTUM, which has been taking place concurrently since 2022, provides a dedicated platform for what is probably the most exciting field of the future in photonics at the moment: quantum technology and its wide range of potential applications.

As well as the exhibition areas, the trade fair offers a comprehensive supporting program with application-oriented presentations, awards, start-up programs, guided tours, and much more. The World of Photonics Congress – the largest gathering of its kind in Europe – is also part of the fair. It is made up of several scientific conferences hosted by organizations that are global leaders in their fields.

LASER World of PHOTONICS is organized by Messe München and has taken place every two years since 1973. The next trade fair and congress will run from June 25-30, 2023, in Munich – from now on co-located with automatica, leading trade fair for automation and robotics, whose range of exhibits perfectly complements the trade fair. LASER World of PHOTONICS has also built up an international trade fair network and every year it organizes high-profile regional fairs for laser and optical technologies in China and India.

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LASER World of PHOTONICS

Messe München

German Industry Association SPECTARIS

SPECTARIS is the German industry association for optics, photonics, analytical and medical technologies

SPECTARIS represents more than 400 innovative companies. Well-known representatives include Carl Zeiss, Jenoptik, Leica, Rodenstock, Dräger, Sartorius, Karl Storz, Otto Bock, and Eppendorf. But the majority of member companies are medium-sized manufacturers that are often considered ’hidden champions’ in their fields on the global market.

SPECTARIS brings together fascinating, forward-looking, and innovative industries: Consumer optics (ophthalmic optics), photonics, analytical and medical technologies.
Together, these industries have generated total revenues in 2021 of close to 78 billion and employed 313,000 staff.

The medium-sized company structure, its vast potential for innovation, and its clear focus on exports are the common factors of these industries, whose product solutions are used across a range of different industries, often as key technologies that provide people with a high quality of life.

SPECTARIS is a powerful network which facilitates a constant exchange between its members while providing a platform for discussions with politicians, other associations, important users, and sales agents. As a service provider, SPECTARIS not only ensures that its members have access to valuable market and industry data but also provides targeted assistance for sales staff as well as information regarding permits, important legal amendments, and economic matters.

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SPECTARIS
German Industry Association for Optics, Photonics, Analytical and Medical Technologies

Tematys

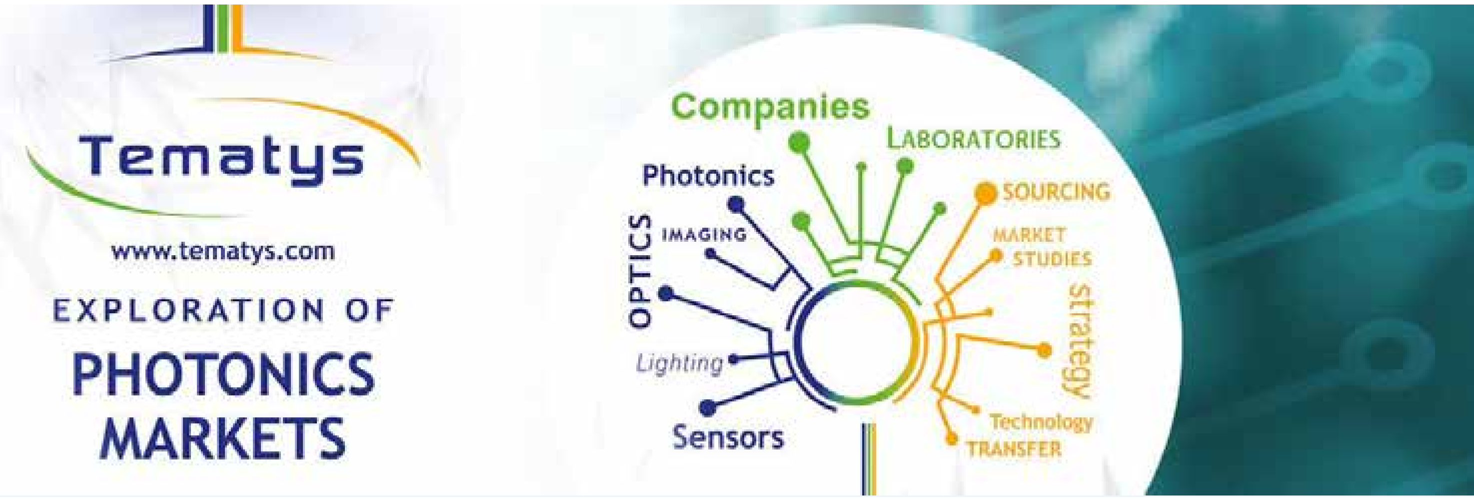
Explorer of Photonics Markets

TEMATYS is an independent, medium-sized consultancy firm, which focuses on studies and strategies in the areas of optics, photonics, sensor technology, imaging, quantum technology, and their applied markets. We have a particular expertise in technologies transfers, R&D exploitation, and the marketing of emerging technologies.

We assist with the critical steps of the product development process and offer services that go beyond market studies. One example of this is customer needs analyses on the exact, demand-based development of products.

We offer end users tailored market updates and procurement services in numerous applied markets for the technologies described above. Examples include life science, security, and aviation.

TEMATYS offers associations, industry clusters, and public institutes information to facilitate strategic decision-making. We have more than 200 international customers in Europe, Asia, and the USA, including research organizations, public institutions, company groups, industry consortia, SMEs, and start-ups.



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