SFI Digital Food Quality

ANNUAL REPORT 2024

DigiFoods

• **Cover** Photo/cc: Marianne Bakken, SINTEF

Vilde Vraalstad wearing eye tracking glasses while picking tomatoes at Wiig gartneri, to investigate how human demonstration can help train artificial intelligence.

• Photo/cc: Jens Petter Wold, Nofima

Measurement of cherry tomatoes on conveyor belt.

Colophon
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Annual Report 2024.
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Contents

1. Overall progress and summary for 2024

DigiFoods is a Center for Research-based Innovation, funded by The Research Council of Norway (RCN) and the partners. DigiFoods is developing smart sensors for effective food quality assessment directly in the processing lines and in field.

The intention is that massive assessment and digitalization of essential food quality parameters will be used for optimization of processes and value chains and make the food industry more efficient and sustainable. This research is in the very exiting intersection of food science, sensor technology, process control, robotics, and data analysis, and gives rich opportunities for innovation at different levels.

DigiFoods started at the end of 2020 and is now, after four years, halfway. Most activities are progressing well, and industry partners are active in the work. The centre is organized in four main activities (pillars) including

1. sensor development,
2. integration of sensors and robotics,
3. in-line implementation and testing, and
4. utilization of large-scale sensor data from foods.

This organization works as intended: New sensors developed in one pillar are incorporated in the research in other pillars. Novel in-line methods developed earlier years, are adapted, and used to collect large-scale quality data for process understanding and improvement. This kind of progress is motivating and illustrates the added value of being a center rather than several stand-alone projects. It gives us the opportunity to think and act long-term and interdisciplinary.

The annual meeting with all partners was held in Gjøvik in May, where we visited HOFF's large and impressive French fries production plant. The process is rather complex and DigiFoods has done work to combine in-line NIR with other process settings in an effort to improve control. The annual meeting was as always important for sharing results, ideas and planning further work. The spirit was high and motivation strong, as we all saw that we have achieved a lot together and obtained fine and promising results. We have even achieved real innovation in some companies.

2024 was a good year for DigiFoods. We conducted small and large measurement campaigns in the process lines. Some lasted a day, others took weeks. We thank the companies for opening the doors, providing technology, and engaging in this kind of work. This sort of activity is the core of DigiFoods, where we can learn about the products and processes, consider the challenges, develop and test the sensors, gather the partners to discuss the results, and together see potential innovation ahead.

Our work was structured into twelve research projects, spanning topics from sensor and application development to robotics, process analysis and consumer demands. Scientific highlights have been many, the level of innovation in the research is high, and we have contributed to real innovation in the companies.

Scientific highlights have been many, the level of innovation in the research is high, and we have contributed to real innovation in the companies

Photo/cc: Wenche Aale Hægermark, Nofima

The DigiFoods consortium gathered for the 2024 Annual meeting in Gjøvik.

Fourier-transform infrared spectroscopy (FTIR) shows promise for measuring protein composition in peptide blends from enzymatic hydrolysis, and there is currently no industrial solution for such measurements. A portable FTIR instrument, both developed and built in DigiFoods, has now been tested with excellent results, enabling industry measurements, improving the understanding and control of these bioprocesses. Bijay Kafle defended his PhD in June 2024, where he investigated how FTIR can be used for efficient characterisation of protein hydrolysates. He also showed how the same approach can be used in analysis of milk protein composition, and currently there is work underway for characterisation of fermentation processes and microorganisms. We have continued our work on miniaturization of IR technology based on new types of LEDs (light-emitting diodes) and semiconductor lasers. This will allow for small handheld sensor systems for measuring chemical properties in foods throughout the value chain. Prototype systems will be evaluated on different foods in 2025.

We have demonstrated that Raman is suitable for determination of various food quality attributes of heterogenous foods directly in industrial processes. We are now benchmarking Raman against NIR spectroscopy with respect to robustness regarding variation in sample structure, as well as cost of calibration and calibration maintenance. Hyperspectral camera technology has been developed for industrial measurement of fat, pigment, blood and melanin spots in salmon fillets and the technology was put into commercial use in 2024. The technology is interesting for several different quality measurements on fish and meat, and we have also studied opportunities within sweetness measurements in fruit and greens.

We have developed a new NIR sensor for non-contact sub-surface measurements. It can be used for sugar measurement in strawberries in the field and in tomatoes on a packing line. The NIR sensor has demonstrated potential for in-line assessment of core temperature in fish cakes and meat content in king crabs. A commercialization project for this technology is ongoing.

An important activity in the center is to conduct in-line measurements in industrial processes, and we have worked on the following cases: Dry matter in potatoes, dry matter in cheese, core temperature in fish cakes, fat content in sausages and beef loins, fat and protein in poultry and salmon by-products, as well as quality attributes in salmon fillets.
All these methods are novel and can significantly contribute to process improvement. The food companies learn about the process variations, leading to improvements in some processes, with the goal of reducing waste and achieving consistent final quality. In 2024 we collected in-line spectroscopic and other process data from TINE, Nortura, Norilia, HOFF and Lerøy. This has given an increased understanding of the processes and quality variations, and for TINE, the strategy has produced lasting innovations that contribute to increased profitability and better utilization of incoming milk.

In 2024 we had ten PhDs/post-docs connected to DigiFoods. We also recruited 4 master students who contributed to our work. Our students are well integrated in the different projects and contribute to many of the centre results and dissemination.

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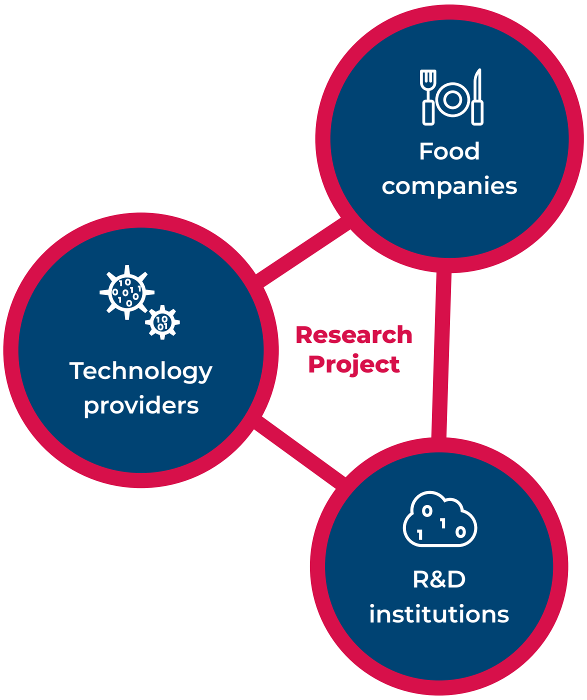


DigiFoods innovation model: Each research task assigns active partners from all three groups: Food companies, technology providers and R&D institutions. Together they will
i) consider the needs and business cases,
ii) develop and evaluate technology and
iii) implement and commercialise.

In this annual report we present the main work and results achieved in 2024. Interesting highlights from the research are presented in more depth. Our novel and versatile NIR sensors have been tested out in the industry on tomatoes, fish cakes and king crabs, and you can read more about the motivation behind this. The work on FTIR spectroscopy is promising and we can now outline potential directions for commercialization. You can also pick up thoughts about how we, in today's world of never-ending data, can make clarity out of chaos.

We hope that you will enjoy the annual report 2024.

Jens Petter Wold
Centre Director, SFI DigiFoods

Article

From chaos to clarity

by Wenche Aale Hægermark, Nofima

Analysing data is about transforming vast amounts of data into meaningful patterns and insights. This is the daily life of senior scientist Ingrid Måge at Nofima.

Photo/cc: Joe Urrutia, Nofima

"It motivates me to find structure in large datasets and to understand connections in what seemingly appears as chaos," she says.

It is primarily the food industry that benefits from Ingrid's expertise. The goal is to gain better insight into how various factors affect both the process and the product.

The Taste of Norvegia Should Not Vary

Ingrid has worked with TINE and cheese in several projects since the early 2000s. With a fresh master's degree in chemometrics, she started a PhD in a project aimed at improving production processes in Norwegian food companies.

The collaboration with Tine has continued. The goal of the research carried out in DigiFoods is to understand quality variations, why they occur, and what can be done to ensure consistent cheese quality. Many factors can affect quality, including the composition of milk components. These may vary with breed, season, weather, feed, and lactation, i.e., how long it has been since the cow calved. Additionally, everything that happens on the processing line also has an impact.

"Previously, TINE manually took spot samples of the cheese for laboratory measurements. Now, they have installed an NIR sensor that measures all the cheeses inline. This gives us access to much more data, and together with information about the milk composition and process data from the processing line, we have gained new insights. Among other things, we have found out which process parameters matter the most, and based on that, TINE has made adjustments to the processing protocols," Ingrid explains.

Utilizing the Whole Chicken

"A key driver for me is respect for raw materials. We must ensure that we utilize them to the maximum, and use as much as possible for food," says Ingrid.

This is the core of Norilia's business, which owns Bioco – Norway's only facility for converting residual raw materials from chicken and turkey into high-value ingredients. The goal is to produce protein ingredients with consistent, high quality and neutral taste that can be used in food production. One challenge is that the composition of this raw material varies. For example, there is a difference in the distribution of nutrients in residual raw materials from turkey and residual raw materials from chicken, and in the skin versus the meat left on the carcass.

"To make a good protein product every time, we must either ensure that the raw material mixture is as similar as possible each time or know exactly how to adjust the process when the raw material varies. We also need to understand how different enzymes affect the quality of the protein powder. This is where data analyses come in. We analyze the data collected during the process, from the NIR sensor that

Photo/cc: Christian Thorjussen, Nofima

Ingrid Måge visits a chicken farm to learn about husbandry practices and data collection methods.

measures the amounts of fat, proteins, and bones in the raw material to the protein product after the enzymatic hydrolysis process," Ingrid explains.

Data Analysis and Animal Welfare

Nofima has been working with both spectroscopic measurement methods and data analysis for several decades. Data analysis often involves linking sensor measurements with other data. It is these combinations of data from different sources that make it possible to find connections between several different factors.

In DigiFoods, one of the PhD students has investigated how feed type affects the occurrence of ascites, which is a health condition in broiler chickens. To conduct these investigations, Nortura has extracted a large dataset from its database, with information on over 6000 chicken flocks from 250 different farmers.

"There are many different factors that affect the occurrence of ascites. To calculate the effect of feed type, it is necessary to include data on both feed, air quality, and growth in different phases of the chicken's life. By considering all these factors and how they interact, he has found that some types of growth feed pose a slightly higher risk of ascites than others," explains Ingrid Måge.

Data Analysis Today and in the Future

Data analysis has gone from being seen as something boring and dry to a field that is really in vogue and that many want to work with. At the same time, Ingrid can tell that the workdays are surprisingly similar to how they were when data analysis was considered boring. Today, she has far more algorithms available for machine learning, but the biggest challenge is getting enough good data.

"It help to have a lot of data if it isn't fit for purpose. Modern food production generates vast amounts of data, and the industry has become more aware of the importance of both collecting and structuring data. Many companies invest significant amounts in digital data platforms, expecting insights that they can use to develop processes and products," says Ingrid.

At the same time, Ingrid points out that there is a hype that gives the impression that artificial intelligence can be used for everything. But even though developments in language models and automated image and video analysis have come a long way, these technologies cannot necessarily be used directly to analyze process and product data in the food industry.

"Another development is the closer connection between statistics and mathematical modelling. Such hybrid modelling can provide more precise answers and predictions even for complex issues," concludes Ingrid.

"Modern food production generates vast amounts of data, and the industry has become more aware of the importance of both collecting and structuring data"

Ingrid Måge, senior scientist, Nofima

Photo/cc: Karen Wahlstrøm Sanden, Nofima

SenseInside measuring meat content in brown crab.

Vision and objectives

The goal of SFI Digital Food Quality is to develop smart sensor-driven solutions that deliver the essential food quality information required for successful process optimisation and digitalization of the food industry.

Food processes are extremely complex and challenging to measure due to the inherent high level of biological variation in raw materials. The development of advanced solutions that are built on a fundamental understanding of food science, will allow the food industry to effectively measure and handle these variations, enabling a ground-breaking digital transformation of the industry.

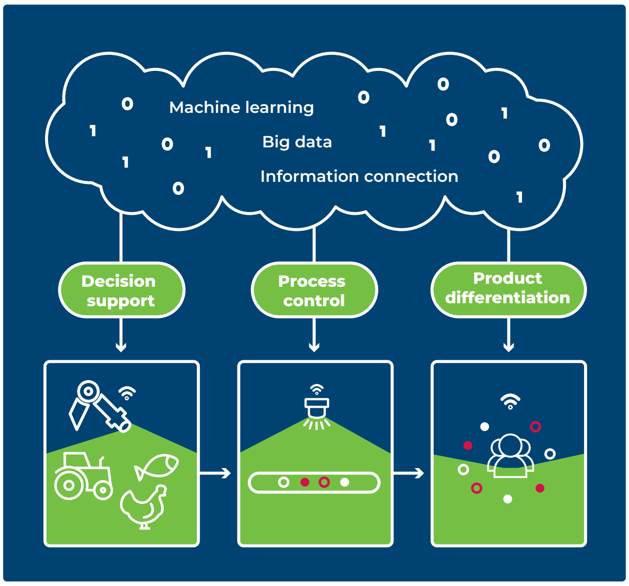
The **Primary objective** of DigiFoods is to develop digital solutions for food quality assessment as cutting-edge technological basis for optimal food value chains.

Besides this there are seven **Secondary objectives**:

1. Develop novel in-line sensor systems and applications for measuring critical food quality parameters
2. Develop automation and robotic solutions for enhanced sensor operations in process and in field
3. Develop solutions and strategies for successful sensor implementation in the food production
4. Develop data-driven strategies for process, product and value chain optimisation based on extensive food quality measurements
5. Build and transfer competence in industry and academia and educate master students, nine PhDs and three post docs
6. Foster innovations, patents and spin out companies by the project partners from food industry, technology and research
7. Disseminate knowledge to the industrial sector, the research community, and to the general public

DigiFoods strives to change food production by enabling optimization, control and differentiation based on measurements of food quality. The results will lead to a more efficient and sustainable food industry, internationally competitive Norwegian technology companies, and enhanced knowledge transfer and researcher training.

The DigiFoods objectives range from fundamental technology knowledge to practical industry and market implementations, which are equally important for achieving successful innovations. We aspire to bridge the gap between research and industry by building a strong, business-oriented research network of innovation-oriented companies, and national and international R&D institutions. These expected impacts are in line with the centre goals and the overall objectives for the SFI scheme.



The DigiFoods vision: Extensive food quality assessment enables new insights and radical changes from farm to fork.

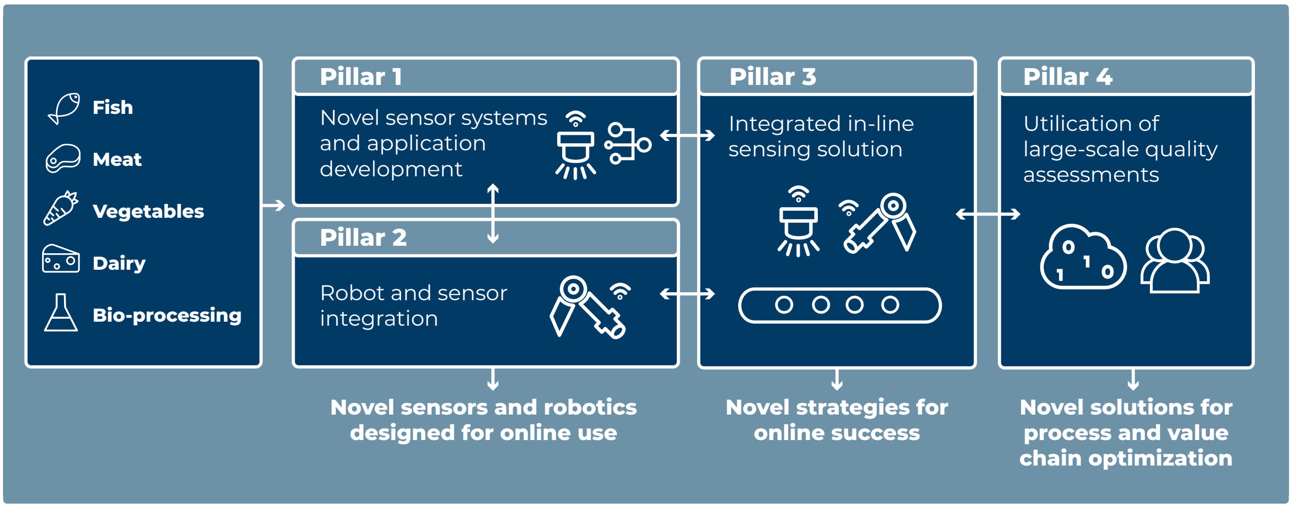
2. Research plan and strategy

The main research hypothesis of DigiFoods is that in-line food quality measurements can be used to understand, optimize, and radically improve food value chains.

The innovations in DigiFoods are accomplished by combining basic and applied research. A major difference from traditional research in this area lies in the scientific method; prototypes are being tested at the end-users at an early stage, as part of the technology development. This includes large-scale trials in fields, onboard fishing boats and in industrial food process lines, and secures relevance and industry involvement. The research activities are organized in four pillars, and involves value chains for fish, meat, vegetables, dairy and bio-processing. These pillars are not closed; most activities straddle two pillars or more and others have progressed from one pillar into another.

Pillar 1 is developing novel sensor systems that address critical in-line challenges and industrial needs. Pillar 2 is designing novel integrations of robotics and sensors. Pillar 3 is developing strategies for successful implementation of in-line sensors in processes. In Pillar 4, the in-line food quality measurements are placed in a broader perspective and combined with other relevant data sources to realize improvements at farm, industry and value chain level.

Most of the experimental work in Pillar 3 and 4 is taking place in the food industry or in the field. These serve as important research facilities for securing relevance and usefulness of the technology, and for collecting extensive amounts of food quality data.



Partner companies representing the major food value chains will define relevant research activities for the four research pillars.

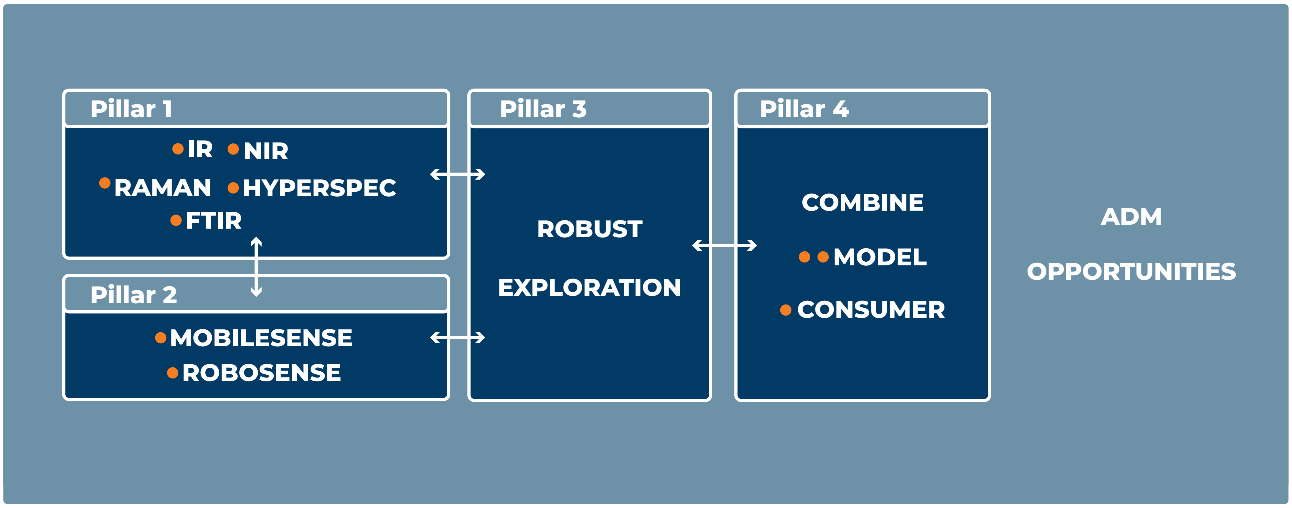
The research activities are organized in four pillars, and involves value chains for fish, meat, vegetables, dairy and bio-processing

All activities do as far as possible include participants from all three partner groups (food companies, technology providers and R&D institutions) to ensure practical relevance, interdisciplinary and relevant competence. This project organization is the core of the centre's innovation model, meaning that the partner groups together are considering business cases and innovation opportunities associated with the research.

To implement the research, we have divided the activities into research projects, twelve in 2024. The projects address the outlined goals and envisioned innovations, targeting gaps in knowledge and technology.

All partners are involved in the planning of the projects, ensuring relevance, and securing in-kind contributions through active involvement in the ongoing work.

Projects in Pillars 1 and 2 are collaborating to develop prototype solutions and these are being evaluated for industrial use in Pillar 3, together with already existing sensors. Results from Pillar 3 are also be fed back to Pillar 1 & 2 to optimise and improve the solutions based on in-line performance. Well working solutions developed in Pillar 3 provide Pillar 4 with essential quality data on an industrial scale.



SFI projects allocated in research pillars according to the figure on the previous page.

● PhD / Post doc

Article

New method for continuous measurement of core temperature in fish cakes

by Wenche Aale Hægermark, Nofima

A new measurement method can simplify the production of safe and juicy fish cakes. The sensor measures the temperature right to the core without damaging the product, giving producers better control over quality.

At Lerøy Seafood's factory in Stamsund, they produce 160,000 fish cakes per shift. During peak season, they run two shifts.

Currently, there is no commercially available method to continuously measure and control the core temperature. Now, scientists from Nofima and SINTEF Digital are testing whether a spectroscopic measurement method based on NIR (near-infrared) spectroscopy can contribute to better control and more consistent quality.

Balancing Food Safety and Taste

Each cake must have the correct temperature to be safe to eat. The core temperature must be at least 72°C to kill potential pathogenic bacteria, but if it gets too high, the fish cakes lose flavour and become too dry. This can be a challenging balance in large-scale production. To be on the safe side, producers often choose to maintain a higher temperature than necessary.

"With continuous measurements, we can see over time how the core temperature varies throughout the day, week, and month. We can use the findings to optimize the process so that the core temperature becomes more stable. This will give us fish cakes with more consistent quality," says Steffen Andersen at Lerøy.

From Trials at Nofima to the Factory in Stamsund

The development of the new measurement method started in Nofima's Meat Pilot Plant. Here, Meat Specialist Tom Johannessen made fish cakes according to Lerøy's recipe. These were cooked at different temperatures and cooking times to achieve various core temperatures.

Then, scientists measured the core temperature with both a traditional insertion thermometer and the NIR sensor.

"We compared the NIR measurements with traditional thermometer measurements and found a very good correlation. The promising results made it natural for us to proceed with larger-scale testing at the Lerøy factory," says Jens Petter Wold, senior scientist at Nofima and head of SFI DigiFoods.

Measuring Deep Inside the Product

The NIR sensor was mounted on the production line in the factory, above the conveyor belt where the fish cakes come out of the oven. It can measure the temperature in each fish cake that passes. The special thing about this NIR technology is that it can measure right to the core of the product.

Photo/cc: Lars Erik Solberg, Nofima

Heat treating fish cakes.

To get accurate measurements, it is important to measure in the right place. The temperature of a single fish cake coming out of the oven can vary greatly. The temperature at the edges can be 8–10 degrees higher than the temperature in the middle, so it is important to measure in the centre of the cakes, where the temperature is lowest.

"Using this type of technology is not just about making production more efficient. It is also about producing safer food with better quality and less waste,"

Jans Petter Wold, Centre Director, SFI DigiFoods

Photo/cc: Jens Petter Wold, Nofima

Lars Erik Solberg studying fish cakes under NIR measurement.

Reducing Waste and Saving Energy

Today, operators regularly insert thermometers into samples of fish cakes. This is not only time-consuming, but it also destroys the products being measured. With the new technology, Lerøy can continuously monitor the temperature without wasting a single fish cake.

There can be waste if the core temperature of the fish cakes does not reach 72° C. "If the temperature is too low, and we discover it quickly, we can heat them up again, but if the fish cakes have already been sent for cooling, it is too late, and then there is waste," says Steffen Andersen at Lerøy.

The Future of Food Production

The project shows how new technology can improve traditional food production. The same principles used for fish cakes can also be applied to other heat-processed foods like burgers and steaklets. A limitation here is that the products cannot be too thick, as there are limits to how deep we can measure with NIR.

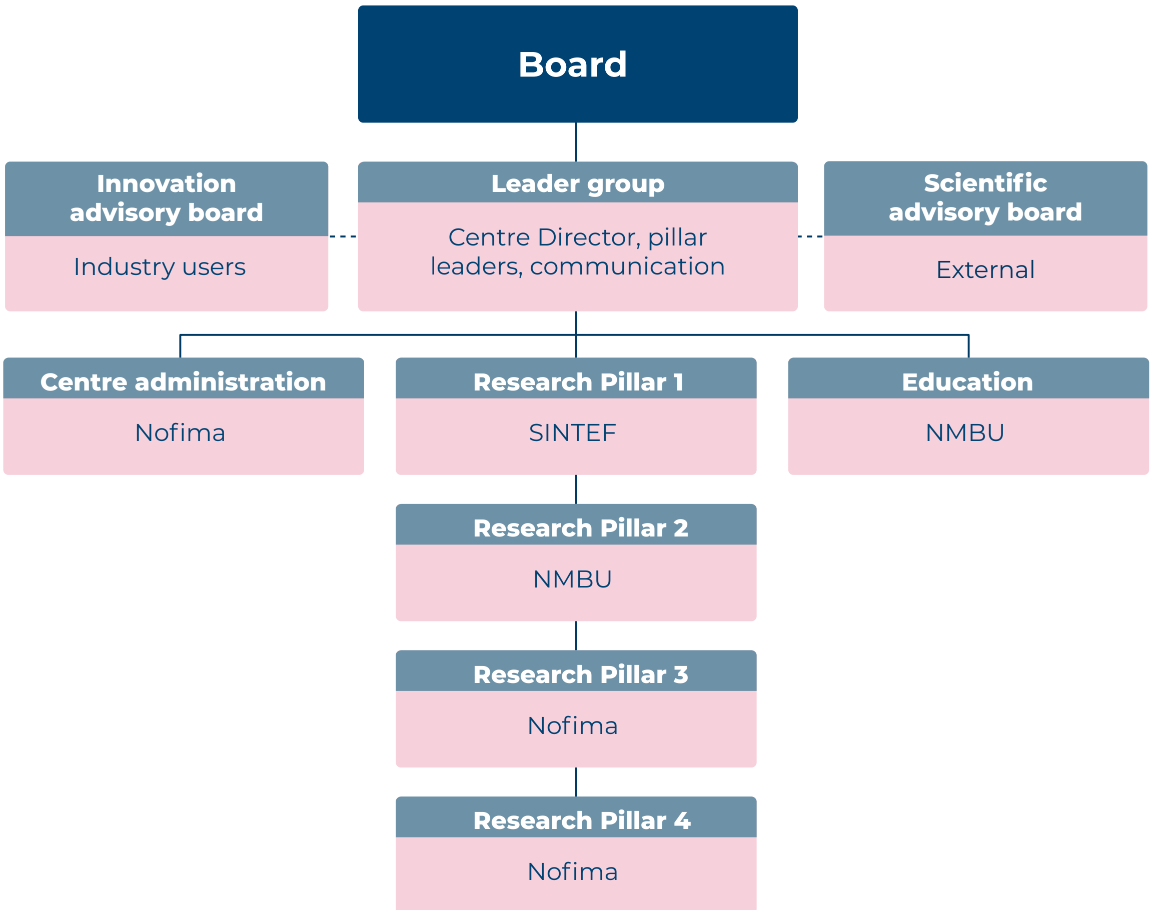
"Using this type of technology is not just about making production more efficient. It is also about producing safer food with better quality and less waste," concludes Jens Petter Wold.

3. Organization

Organizational structure, and cooperation between the centre's partners

DigiFoods has a decentralized organizational structure. It's headquarter is at Nofima, Campus Ås. The food industry is by nature decentralized and the technology companies are also located around Norway. The organization is shown in the figure below.

The DigiFoods Board oversees that obligations are fulfilled, and decide on financial, partnership and IPR matters, as well as ratifying annual research plans made by the leader group. In 2024, the Board met for two physical meetings, one following the Annual meeting in May and one in November. The Board consists of the following elected members (see next page).



Chairperson of the DigiFoods Board

Anne-Cathrine Whist, TINE

Board Member

Jørgen Kvinge, Lerøy Norway Seafoods

Board Member

Silje Ottestad, Maritech

Board Member

Ellen E. Altenborg, BI (representing Saga Robotics)

Board Member

Mats Carlin, SINTEF Digital

Board Member

Anne Cathrine Gjærde, NMBU

Board Member and representing the host institution

Eva Veiseth-Kent, Nofima

The DigiFoods Board.

In addition, Mona Gravningen Rygh, the contact person for DigiFoods at the Research Council of Norway, has an observer status at the board meetings.

The centre scientific work is organised through close collaboration between four Pillars:

- Pillar 1 Novel sensor systems and application development (Lead: SINTEF)
- Pillar 2 Robot and sensor integration (Lead: NMBU)
- Pillar 3 Integrated in-line sensing solutions (Lead: Nofima)
- Pillar 4 Utilization of large-scale quality assessment (Lead: Nofima)

Furthermore, NMBU leads the recruitment and education process in DigiFoods.

The leader group manages and leads DigiFoods, such as ensuring strategic planning and running of projects, recruitment of qualified personnel, providing a good working environment, accounting, dissemination and reporting.

Photo/cc: Reidun Lilleholt Kraugerud, Nofima

The DigiFoods leadergroup, from left: Weria Khaksar, Marion O'Farrell, Ingrid Måge, Jens Petter Wold, Wenche Aale Hægermark, Anne Risbråthe, Stine Thøring Juul-Dam, Nils Kristian Afseth, Kristian Hovde Liland.

The leader group consists of:

- Jens Petter Wold (Nofima) – Center Director, overall scientific and administrative leader
- Marion O'Farrell (SINTEF Digital) – Scientific Manager of Pillar 1
- Weria Khaksar (NMBU) – Scientific Manager of Pillar 2
- Nils Kristian Afseth (Nofima) – Scientific Manager of Pillar 3
- Ingrid Måge (Nofima) – Scientific Manager of Pillar 4
- Kristian Hovde Liland (NMBU) – Manager Recruitment and Education
- Stine Thøring Juul-Dam (Nofima) – Centre Coordinator
- Wenche Aale Hægermark (Nofima) – Communication Leader
- Anne Risbråthe (Nofima) – DigiFoods Controller

The Scientific Advisory Board (SAB) for DigiFoods, consists of researchers with competencies in the fields of research in the centre. An important task for the SAB is to review results and research plans and give advice on research methodology and industrial and societal relevance. The members are:

- Prof. Søren Balling Engelsen, Dept Food Science, Univ. Copenhagen
- Prof. Bjarne Kjær Ersbøll, Dept. Applied Mathematics and Computer Science, Technical Univ. of Denmark
- Ole Alvseike, Head of division Animalia, Norway
- Onno de Noord, Advanced Data Analysis Consultancy, Amsterdam

The centre also has an Innovation Advisory Board (IAB) with representatives recruited from user companies. The members oversee, evaluate and advice on how innovation processes arepromoted and incorporated in the research activities, including knowledge transfer, learning and innovation arenas, as well as industry involvement and business case development.

Photo/cc: Marion O'Farrell, SINTEF

Our Scientific Advisory Board gathered for a two-day review of the research in DigiFoods. From left: Onno de Noord, Bjarne Kjær Ersbøll, Søren Balling Engelsen and Ole Alvseike. Centre Director Jens Petter Wold to the right.

The members are:

- Silje Ottestad, Maritech
- Piotr Chylenski , Norilia
- Per Berg, Nortura
- Roy Martin Hansen, Lerøy Norway Seafoods
- Ellen Altenborg, BI (representing Saga Robotics)

DigiFoods is organized to facilitate excellent collaboration between three groups of partners: R&D institutions, food companies and sensor, robotics and digital platform companies. The user partners are as far as possible involved in the planning of experiments, execution, and discussion of results. Research is conducted in the end-users process lines and requires that scientists, engineers and user partner personnel are involved.

Frequent meetings are organized at Board level (each six months), Centre level (annual meetings), leader group (every third week), with IAB (once a month) and thematic or project level (as required). In addition to physical and digital meetings, DigiFoods has an internal SharePoint site with a news feed where centre participants can post e.g. news, links to documents, research plans, results, pictures and videos. The SharePoint will also act as a social media, thus contributing to build the DigiFoods team spirit. DigiFoods is also sharing news on Linkedin.

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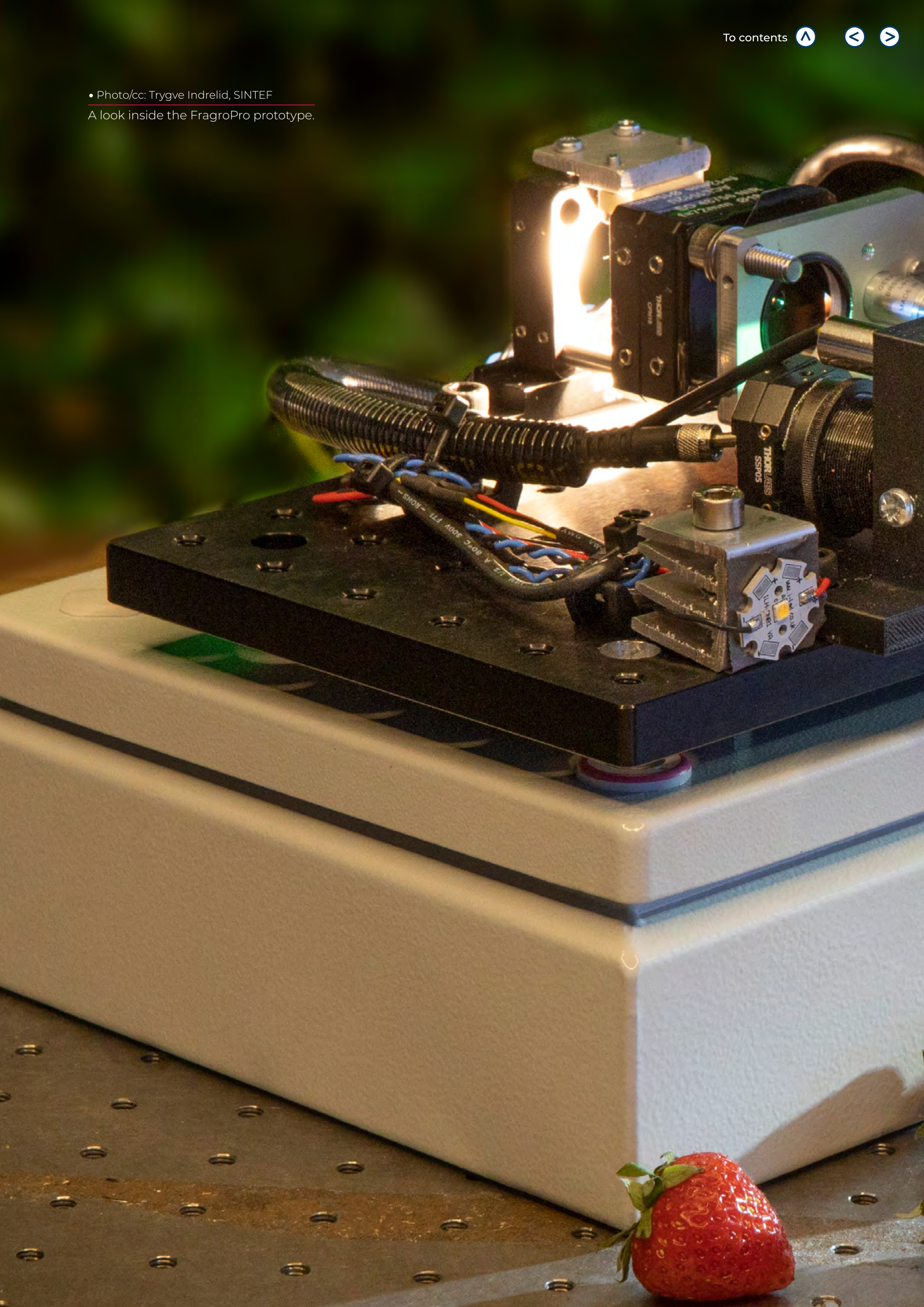
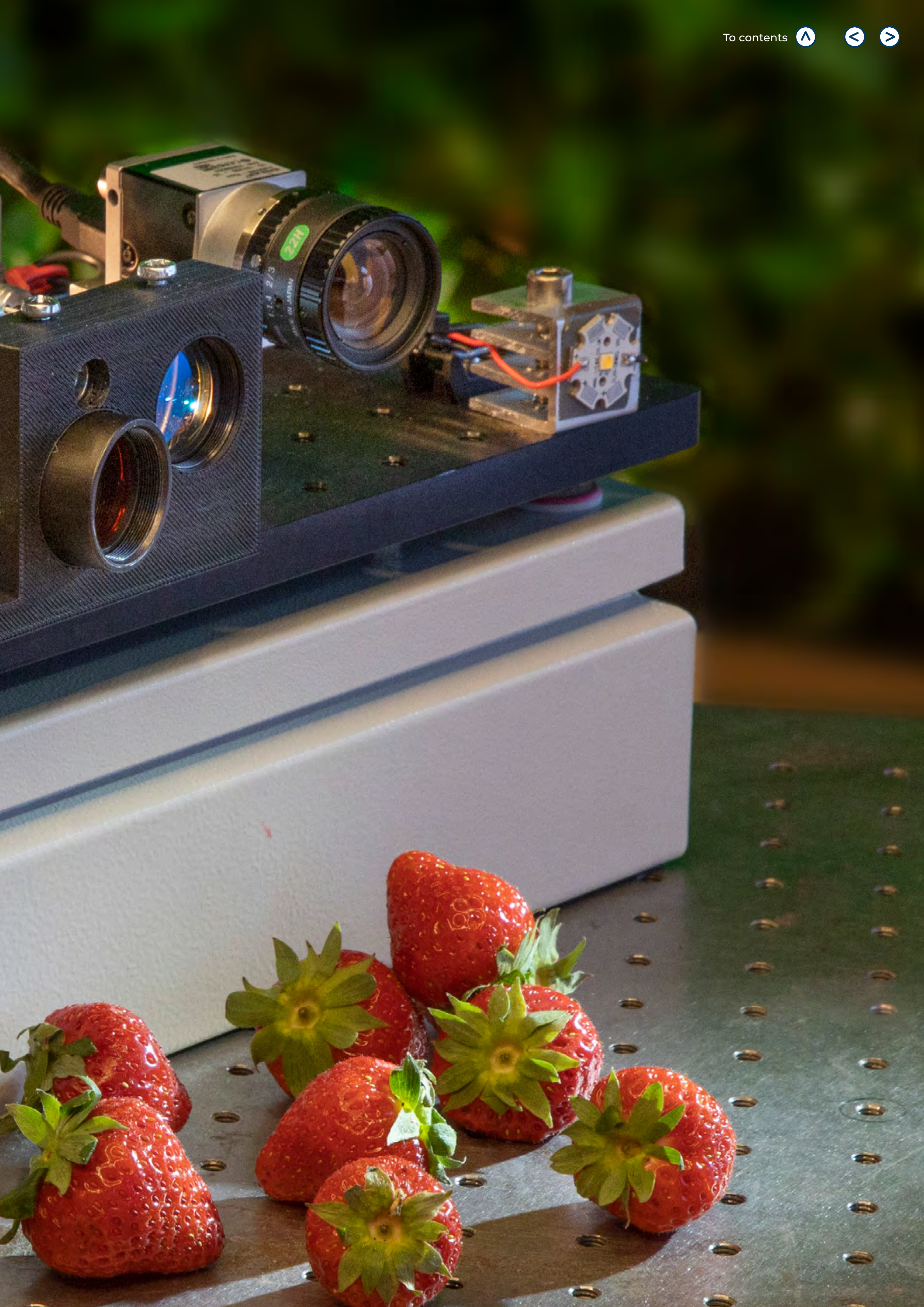


• Photo/cc: Trygve Indrelid, SINTEF

A look inside the FragroPro prototype.



Partners

Research partners

Nofima is one of Europe's largest institutes for applied research within the fields of fisheries, aqua culture and food. Nofima's vision is "Sustainable food for everyone", while our objective is to actively contribute to solve the large social challenges such as increased food security, better food safety and health, reduced food waste and reduced environ – mental and climate footprints. We have excellent knowledge in food quality science and are recognized for our research on applied bio-spectroscopy, rapid spectroscopic measurements of food quality, for multivariate data analysis and consumer science over the last 30 years. Nofima is the host institution of DigiFoods and is contributing with peak expertise in applied spectroscopy (Raman, NIR, fluorescence, FTIR and hyperspectral imaging), process analytical technology, data analysis, consumer science and food science. Nofima also provides an extensive state-of-the-art lab for spectroscopic analysis, food pilot plants and food technology labs. Our key personnel contributing are DigiFoods' Centre Director Dr. Jens Petter Wold, Centre Coordinator Stine Thøring Juul-Dam, Pillar 3 Lead Dr. Nils Kristian Afseth, Pillar 4 Lead Dr. Ingrid Måge, Dr. Karsten Heia, Dr. Lars Erik Solberg, Dr. Erik Tengstrand and Dr. Paula Varela. A group of about 16 scientists and technicians are also taking part in the research.

University of Lincoln has established an international reputation for the quality of its research and teaching in agri-robotics. The research undertaken is strongly applied, and it has many links to the local, national, and global agri-food industry. The research facilities include dedicated campuses for agriculture and food manufacturing. Our main contribution to DigiFoods is to provide world-leading expertise in agricultural robotics. Our team is involved in the MOBILESENSE project supporting the NMBU team in the deployment of mobile robots in real agricultural environments. Our team provided a navigation system software and digital twin of the strawberry farm together with technical assistance to enable the NMBU team the deployment of the Thorvald robot in strawberry polytunnels. The team also actively participates in seminars and project meetings. The University offers further opportunities for the project consortium and will welcome researchers and practitioners from industry to spend time in Lincoln with the objective of strengthening collaboration within the centre. Our key personnel contributing to DigiFoods include Katherine James, Prof. Simon Pearson and Prof. Grzegorz Cielniak.

Ulm University (UULM) is ranked #19 among German Universities and overall #199 in the world (Times Higher Education Ranking 2025). The Institute of Analytical and Bioanalytical Chemistry (IABC) is leading several national and international projects dedicated to the development of advanced vibrational spectroscopic sensing concepts for industrial, medical, environmental, and food quality /safety applications. In DigiFoods, IABC provides expertise in food quality and safety monitoring /sensing technologies, sensing networks, and data mining via advanced analytical techniques and strategies developed at IABC ensuring food safety and public health. Especially, IABC@UULM develops miniaturized mid-infrared sensing platforms based on a wide variety of infrared spectroscopic techniques (FTIR, ICLs, QCLs, IC-LEDs) combined with thin-film waveguides for analyzing relevant food constituents, contaminants and (bio)pathogens. We anticipate that this collaborative effort will result in the submission of joint publications and the development of further collaborative research projects. Our key personnel contributing in DigiFoods are Professor Boris Mizaikoff and his team members working in the field of food analysis. In addition, the partners in Ulm have started an Applied Research Institute – Hahn-Schickard Ulm – focused on translating fundamental research concepts into real-world practice, which directly contributes to the goals of DigiFoods.

Norges miljø- og biovitenskapelige universitet

NMBU's mission is to contribute to the well-being of the planet through interdisciplinary research and study programs that generate innovations in food, health, environmental protection, climate, and sustainable use of natural resources. NMBU aims to educate outstanding candidates, perform high-quality research, and create innovation.

Two research groups from the Faculty of Science and Technology at NMBU are involved in DigiFoods: the Biospectroscopy and Data Modeling group (BioSpec group) and the Robotics group. The BioSpec group collaborates with the University of Ulm, nanoplus, and OptoPrecision to develop and apply novel handheld and portable infrared devices for food quality measurements. Three prototypes for portable instruments have been established at NMBU. Two prototypes, based on a tunable laser developed by nanoplus, measure samples in liquid form on a waveguide surface and as dried films. Industrial versions of these prototypes are being developed and tested with Biomega. A third prototype, developed by OptoPrecision, enables transmission measurements of liquids.

The Robotics group specializes in agricultural robotics and develops autonomous robots for food processing automation, spectroscopic measurements, and data collection. They are responsible for the RoboSense and MobileSense projects. The RoboSense team developed an autonomous robotic Raman spectroscopy system for in-line Omega-3 fatty acid content measurement in salmon fillets. The system uses computer vision, AI-based learning, and motion planning algorithms for faster and more accurate measurements. The MobileSense project uses a mobile robot platform, Thorvald, with a robotic arm for long-term in-field sensing, collecting sugar-content data from strawberries using FragoPro technology developed by SINTEF.

Key NMBU staff is Professor Achim Kohler, the leader of the project Infrared Spectroscopy, Associate Professor Antonio Leite, the leader of the project Robosense, Associate Professor Weria Khaksar the leader of the project Mobilesense and Professor Kristian Hovde Liland from the department of Mechanical engineering and technology management is responsible for the education of master students.

SINTEF

SINTEF AS Smart Sensor Systems has been developing in-line sensor systems for industry, including the food industry, for more than 30 years, resulting in many process-applied publications and patents of international relevance. SINTEF has specific competence in designing optical measurements systems, based on e.g. spectroscopy, x-ray or cameras and data analysis. A core part of the research involves designing and building robust optical measurement prototypes based on novel measurement concepts, moving as quickly as possible from the lab to the field, and gaining a fuller understanding of the industrial measurement environment. In DigiFoods, SINTEF contributes by designing and building new sensor prototypes for measurement in industrial processes or in the field, and adapting existing scientific instrumentation to industrial sites for inline process characterisation measurements. SINTEF works closely with the PhD students in DigiFoods so that they have a greater understanding of the theory behind the sensor prototypes, and make modifications as required. Our key personnel contributing in DigiFoods are Pillar 1 Lead Marion O'Farrell, Senior Researchers Jon Tschudi, Kari Anne Hestnes Bakke, Anders Hansen and Trine Kirkhus and PhD student, Vilde Vraalstad.

The Universitat Politècnica de València (UPV)
For another year, and 13 years in a row, QS World University Rankings has once again included the Universitat Politècnica de València (UPV) among the 500 best universities in the world. This result joins those obtained by the UPV in the other two main university rankings in the world: ARWU (popularly known as the Shanghai ranking) and THE (Times Higher Education). In its most recent edition, Times Higher Education recognizes the UPV as one of the 200 universities with the greatest social and economic impact in the world.

On the other hand, ARWU, considered the most prestigious ranking internationally, highlights the UPV as the best polytechnic university in Spain and includes it, for the 19th consecutive year, in its global ranking of the 500 most important universities in the world. UPV is particularly relevant in the areas of Engineering and Sciences and a national leader in patent license income and start-up creation. The Multivariate Statistical Engineering Research group was established with the aim of offering the scientific community and the business & technological enterprises a working environment in which to develop research, development and innovation (RDI) in the area of multivariate statistical techniques for quality & productivity improvement. The group is active in Data Analytics, Six Sigma, Industrial Statistics, Process Analytical Technology (PAT), Multivariate Image Analysis (MIA), Process Chemometrics and Statistical Methods for Process Improvement and Optimization.

DigiFoods allows us to share our experience working with industry and research-based innovation. In addition, it is an excellent opportunity to be exposed to the needs of the high-tech food industry, opening new research lines to get involved. UPV is providing joint supervision with NOFIMA of one PhD student on data analytics and real-time process control & optimization. Our key person contributing in DigiFoods is Professor Alberto J. Ferrer-Riquelme.

Food companies

TINE

TINE SA is Norway's largest producer, distributor, and exporter of dairy products, with a rich heritage dating back to 1856. As a farmer-owned cooperative, TINE is committed to producing high-quality dairy products while ensuring sustainability, innovation, and value creation for its owners and consumers. The company offers a diverse portfolio, including cheese, milk, yoghurt, butter, cream, desserts, and ready meals, with strong brands both in Norway and international markets.

TINE is committed to sustainability, health, and responsible value creation, aiming to reduce emissions, improve animal welfare, and ensure resource-efficient production. By focusing on quality, sustainability, and innovation, TINE continuously enhances its production processes and supply chain efficiency. Through DigiFoods, TINE invests in research and technology to optimize production of cheese, reduce waste, and improve food quality via digital transformation. DigiFoods utilizes real-time data analysis and large-scale industrial data to streamline production processes, minimize waste, and boost productivity. This initiative has significantly advanced TINE's value chain, particularly in production of cheese, by using NIR sensors and real-time data to enhance quality control and maintain consistent product quality. Additionally, dynamic recipe adjustments based on real-time ingredient variations have helped maintain consistent texture and flavor in ready meals and ice cream production. TINE's commitment to tradition and innovation ensures a healthier and more sustainable future for generations to come. Our key personnel contributing in DigiFoods are Director R&D Anne-Cathrine Whist, Technology specialist in Cheese and Start Cultures Jorun Øyaas, Manager R&D Cheese and Fat Products Kjetil Holstad, Technology Specialist Cheese Kjetil Jørgensen and PhD student Åse Riseng Grendstad.

Nortura bondens selskap

Nortura is the largest brand supplier in Norway in the meat and egg business, our main brands are Gilde and Prior. We are organized as a cooperative, owned by more than 17 000 Norwegian farmers that supply more than 240 000 tons of raw material from all relevant animal species to our slaughter- and processing plants. Nortura slaughters, cuts, refines and develops meat and egg products that are sold to retailers, restaurants, food-services and other food related industry with the aim of creating value for our unit-holders. Nortura has a strong focus on innovation and R&D and is involved in more than 40 National and international research projects. In DigiFoods we concentrate our work on our poultry, beef and pork value chains using sensors and big data. We expect to optimize our production and processing lines and hope to get more value out of our raw material. By optimizing processes and products we will achieve higher yield and less food waste and thereby reduce the impact on the environment. One main goal with participating in DigiFoods is to serve our customers and consumers with high quality products in the future. Our key personnel contributing in DigiFoods are Research Director Per Berg and Technology Manager Hans Christian Gutu.

Wiig Gartneri is a family-owned business that has been passed down through generations since 1937. Today, it stands as one of Norway's largest greenhouse producers. We specialize in growing various tomato and cucumber varieties, which are distributed nationwide. In addition, we operate a packaging facility, a food processing department, a crop production unit, and our own retail store. One of our main products is the Piccolo tomato, for which we are the only licensed producer in Norway and one of 17 in Europe. This tomato is known for its high dry matter content and exceptional sweetness. Our goal is for every customer to experience the same level of quality with each purchase, and our participation in DigiFoods is therefore based on improving the standard of this tomato variety. Together with DigiFoods, we have tested and explored the potential of implementing in-line Near-Infrared (NIR) measurements in production to identify the sugar content. This technology has shown promising results, indicating that NIR can be used to ensure consistent quality. DigiFoods has supported our goal by exploring measurement methods to secure high product standard while also strengthening our network and collaborations with key partners. Moving forward, we aim to integrate different technologies and contribute to the development of quality assurance in the fresh produce industry. Our key personnel contributing to DigiFoods are Production Manager Frode Ringsevjen and Product Development Manager Martine Tjåland.

Norilia refines and sells rest raw materials (plus products) from the Nordic meat and egg industry, thereby contributing to a more sustainable and profitable agriculture. Our biorefinery Bioco uses enzymatic hydrolysis to refine poultry offcuts. There is a large potential for refinement of other raw materials as well, and Norilia has the ambition to implement and industrialize viable processes. This may include new lines using enzymatic hydrolysis on different raw materials, such as bones and offal from pork, beef and lamb, feather or blood, or through fermentation.

In SFI DigiFoods, Norilia made our process line at Bioco available for development and use of new sensor systems and optimization approaches, as well as for pilot and industrial testing. Our collaboration with research partners showed that thorough applying sensor systems like NIR, Raman spectroscopy and dry film FTIR spectroscopy, it is possible to predict the quality of protein hydrolysates based on variation of raw materials and process parameters. This collaboration allowed us to gather knowledge and develop tools that will enable us to optimize and control our processes with the help of sensor systems. Additionally, Norilia established a collaboration with Norsk Elektro Optikk AS (NEO) to investigate and develop novel solutions for wool grading using advanced hyperspectral imaging technology.

Norilia will continue to contribute to DigiFoods with our competence and know-how on enzymatic hydrolysis, raw materials and products (hydrolysates, fats and sediments), and markets (pet food, food and dietary supplements), as well as providing access to Bioco for further research and development. Our key personnel contributing to DigiFoods include Director Business Development Heidi Alvestrand and Chief Advisor Bioprocesses Piotr Chylenski, along with staff at Bioco.

Lerøy Aurora is a world leading company in salmon and trout farming and slaughtering, as well as the manufacture of products based on these raw materials for the consumer market. We have long experience with handling large amounts of fish, both in the fish farms, through the slaughter process and in production of consumer products. Our overall strategy is to secure a sustainable economic future for fish farming and production, both locally and worldwide. DigiFoods represents a unique opportunity to share knowledge and learn from other companies. The possibilities for new knowledge and innovations are very promising and are both of a generic nature (sector independent) as well as specific for our business. Our key person contributing in DigiFoods will be Factory Manager Tore Pedersen.

Biomega was founded in 2000 on the premise of advancing innovative biotechnology to release the full nutritional and functional value of otherwise underutilized side streams from the salmon industry. Biomega's mission is to transform undervalued, food-grade, raw material into premium food and petfood ingredients through accelerated biorefining. Through the DigiFoods project, we have been and will be an industrial test facility for new in-line monitoring solutions, and our expectations is that along the DigiFoods lifespan new online/in-line process monitoring equipment is devolved that could contribute to a more stable production and end-product quality. This far, we have focused on the characterization of the raw material entering our production line, and we are able to distinguish different raw materials by online measurements. In the remaining project period, we will improve the online/in-line measurements of the input to the biorefinery and try to characterize our hydrolyzed protein products. Our key personnel contributing in DigiFoods are CTO Andrew Dustan and CSO Bjørn Liaset.

Hoff SA is Norway's largest potato processing company, processing 1/3 of Norway's potato production. Hoff is producing a range of different potato-based food products and food additives, such as e.g. french fries, mashed potatoes, potato starch, potato glucose syrup and potato spirits. We believe that DigiFoods can help us solve specific challenges related to variations in potato quality, in addition to generic challenges related to technology and data handling. Hoff wishes to make use of in-line measurements (NIR) either at intake of the potatoes or during processing. The NIR measurements will hopefully give us useful information concerning process control which in turn, and in combination with our participation in the projects ROBUST and MODEL, can help us develop a statistical process control (SPC). We also see great value in sharing knowledge and learning from other food companies with similar challenges. Our key person contributing in DigiFoods is Process and Product Development Manager Ingvild Sveen.

Lerøy Havfisk is a large trawler company in Norway. We have long experience in handling large amounts of fish and facing quality challenges in whitefish production, with highly skilled personnel. Our strategy for i-proved handling of fish is making it possible to sort fish into different quality grades. These are key factors, as we see it, in order to secure a sustainable economic future for the fishing fleet and the land-based seafood industry. DigiFoods represents a unique opportunity to share knowledge and learn from other companies. The knowledge and innovations to be generated can be both of generic nature (sector independent) as well as specific for our business. It is hard to see that all outlined innovations can be established without this joint initiative. Our key person contributing in DigiFoods is Operation Manager Odd Johan Fladmark.

Sensor & Robotic

Lerøy Norway Seafoods is Lerøy's quality brand for sustainable white fish caught in the wild – and sourced from the Arctic seas in the north. The very best raw ingredients are picked, processed and packaged, then distributed to markets world-wide. With a history of more than 140 years of fishing in these waters, it is safe to say that our products are the result of developing and preserving a proud craft. Our main activities are within processing for filet products and ready-to-eat meals. Lerøy has high focus on improving the utilization of our raw material and thereby reduce food waste and increase profitability as well as consumer satisfaction. Assessing key quality properties by advanced sensors will help achieving this, and by combining data from different sources – knowledge and improved processes can be obtained. In DigiFoods, we will contribute with user expertise and production lines and we see this as a unique opportunity to discuss innovation ideas and improvements for our quality development work, e.g. sensors that are easy to use, practical and cost efficient. Our key personnel contributing in DigiFoods are Quality Manager Roy Martin Martinsen and Operational Technology Lead Jørgen Kvinge.

NEO Norsk Elektro Optikk AS is a privately owned research company within the field of electro optics. NEO's main commercial interest is within hyperspectral imaging. Our line of hyperspectral cameras (HySpex) is recognized as the most advanced and accurate hyperspectral instrumentation available in the market. Through the SFI we want to develop new methods for applying our hyperspectral imaging technology to different food industry applications and to develop integral customized solutions. We could also be interested in designing dedicated instruments for one or more of the food partners both within imaging and point spectroscopy. Our main contribution to the SFI will be testing the suitability of our instrumentation for measuring different food quality parameters. We have our own camera lab and expertise within data analysis. Rental of instrumentation for use by other partners will also be one of our main contributions. We expect that DigiFoods will allow us to gain a better understanding of the need for spectroscopic information within the food industry and that this will help us identify new commercial opportunities within our field of expertise.

Half-way through the project we have proven feasibility of using our cameras for tomato and wool quality grading, with project partners Wiig and Norilia, respectively. With both partners we will be looking into options for integrating the technology into their production line. We are also working with Maritech to improve data quality through enhanced illumination systems.

Our key personnel contributing in DigiFoods are Applications Specialist Na Liu, Solutions Manager Lars Gidskehaug, Hyperspectral Applications Manager Julio Hernandez, and CEO Trond Løke.

nanoplus focuses on the development of customer specific optoelectronic devices for sensor applications and has significant experience with complex coupled distributed feedback (DFB) laser diodes, but also the GaSb material system and associated challenges like water-free chip processing. nanoplus contributes to DigiFoods by bringing in capabilities and related expertise in the field of ICL and QCL technology. DigiFoods enables us to maintain a strategic position with respect to emerging technology and related market opportunities concerning infra-red emitters in the food industry field, and to related investigations for future device applications in biophotonics. Our key person contributing in DigiFoods is Johannes Koeth.

MarqMetrix part of Thermo Fisher Scientific offers a simple, stable and powerful Raman spectroscopy platform built for field and process applications at a performance level previously available only in costly lab instrumentation.
We make affordable solutions that operate at scale to monitor and control processes in real-time for efficiency and quality optimization.
Our fast and non-destructive sampling technology allows you to simply "touch" a sample to analyze gasses, liquids, solids and slurries. MarqMetrix has years of experience using Raman spectroscopy for analyzing lipids, collagen, and carotene concentrations in salmon fillets and cooking oil.
We are excited about our participation in DigiFoods because it enables close collaboration with food companies and third parties to innovate and broaden the applicability of Raman technology in the food and beverage industry. Our key personnel contributing in DigiFoods are CEO Brian Marquardt, VP of Data Analysis Thomas Dearing and VP of Strategy Marc Malone.

Saga Robotics develops robots for the agricultural domain. We have developed the Thorvald platform which is a modular and completely autonomous robot that carries out a wide variety of agricultural tasks. The modularity of the robot allows us to operate in open fields, greenhouses, and polytunnels where the robot uses advanced sensor systems and machine learning to navigate autonomously in the field. A very specific outcome from DigiFoods is a close collaboration with developers of sensors and tools that have products or can develop new products that they would like to put onto our robots to collect large amounts of data that has not previously been available to farmers or researchers. We look forward to sharing our knowledge and experience in the DigiFoods partner network and see this as a good basis and opportunity to discuss innovation ideas. We also offer an autonomous robot for field trials with sensors. Saga will work on integrating sensor systems on field robots and to test these in the field.

OptoPrecision GmbH is a small, yet leading company in research, development, and production of high-quality optical sensing devices and solutions. Today, we address with our products applications in the chemical and steel industry, security and observation business and also in the pharmaceutical market. The strategic goal of OptoPrecision is to strengthen and expand its business via network activities with research institutes and complementary companies to new fields of applications based on the adaption of already available in-house solutions as well as the joined development of new technologies.

In DigiFoods, we are contributing in terms of developing multi-purpose driver electronics for different infrared emitters (LEDs or lasers) and detection electronics as well as the corresponding embedded software to operate these circuit boards for the development of novel sensing technologies. First demonstrators have been built in 2021 and have been tested together with coworkers from the NMBU and UUlm team in 2022. In particular, we have realized a mid-infrared laser-based spectroscopic measurement setup for analysis of liquid samples. The system can operate different single wavelength lasers and is unique in both its precision and ability to handle larger volumes of liquids in transmission measurements compared to existing spectrometers. The instrument is ready to be tested for liquid food products in DigiFoods. The instrument has been located at NMBU since 2024 and is ready for use for tests in the industry. In general, DigiFoods provides a partner network and an excellent basis and opportunity to discuss, develop and push innovative ideas towards the market. OptoPrecision works closely with NMBU, Ulm University and nanoplus on thetechnology development. Our key person contributing in DigiFoods is Markus Naegele, who is the head of our analytics department.

Digital platforms, software and analytics

aspentech

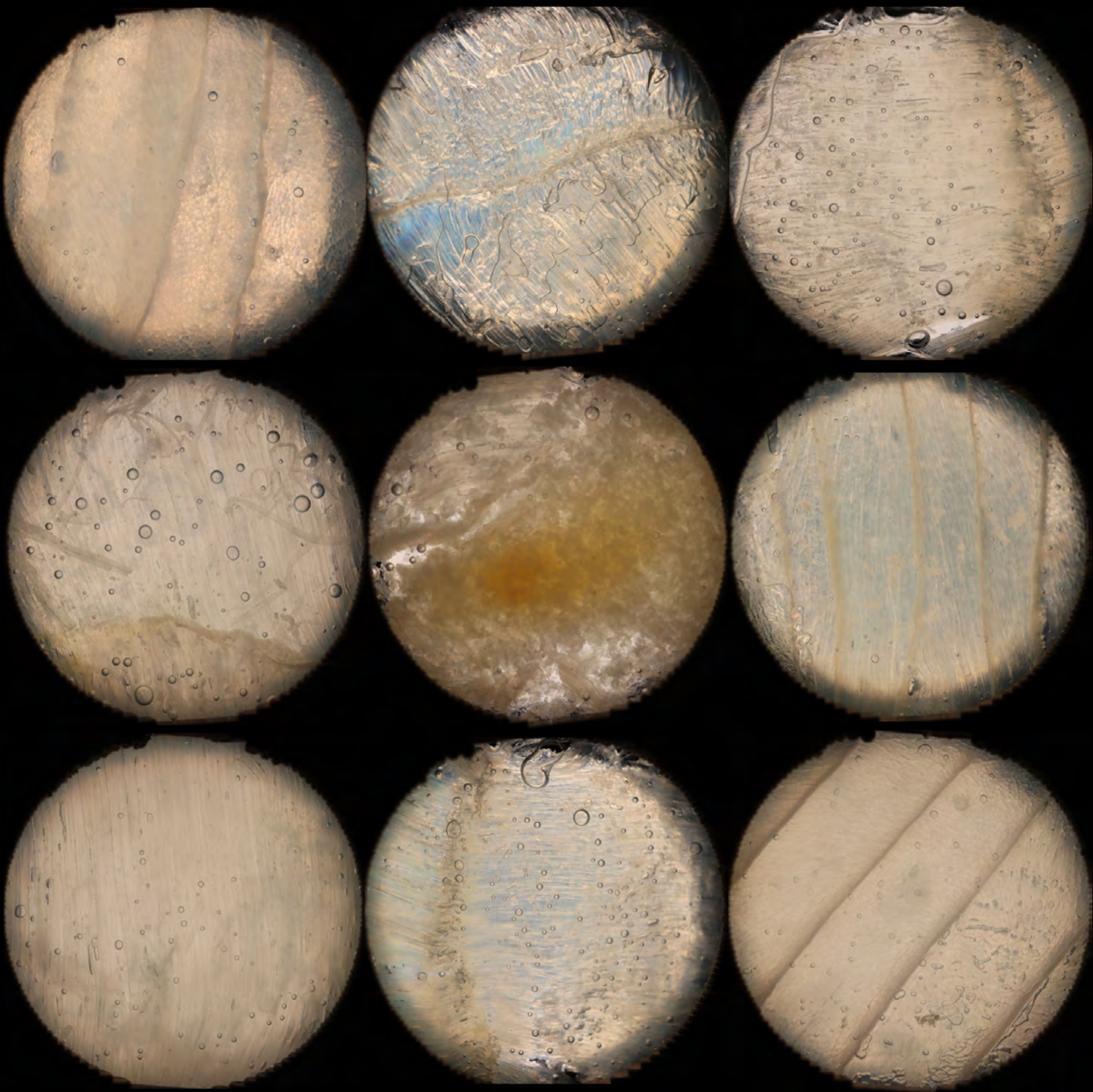
Aspen Technology, Inc. is a global software leader helping industries at the forefront of the world's dual challenge meet the increasing demand for resources from a rapidly growing population in a profitable and sustainable manner. AspenTech solutions address complex environments where it is critical to optimize the asset design, operation and maintenance lifecycle. Through our unique combination of deep domain expertise and award-winning innovation, customers in asset intensive industries can improve their operational excellence while achieving sustainability goals. The DigiFoods Research Centre will address the current knowledge and technology needs to achieve a successful digital transformation of the food industry. This is consistent with the strategies of our organization, where part of our goals is bringing insights from science-based industrial analytics into daily operations. Through the DigiFoods partnership, we will gain valuable insight that will help us guide the development of our solutions so they best fit the needs of the industry.

idletechs

Idletechs AS was founded in order to stimulate the digitalization in the industry. We develop fundamentally new tools combining multi-channel sensors, transparent machine learning methods, and domain knowledge. In DigiFoods we intend to stimulate to deeper understanding, creative innovations and more robust in-line implementations of modern multichannel quality monitoring instruments, as well as to supply software for quality monitoring, deliver thermal and hyper-spectral software in the food production chain and simplify the integration of multichannel sensor data from various sources in the food production sector. DigiFoods will provide important market contacts and user feed-back for Idletechs and enable us to position us in the market. Our key personnel contributing in DigiFoods are CEO Andreas Wulvik and Project Manager Frank Westad.

Maritech is the world-leading provider of seafood software, enabling full traceability, data flow and process support from sea to table. From catch and landing, through production, processing, packing, sales, and logistics. In addition to business systems, packing solutions, data, and IoT, Maritech has specialized in hyperspectral technology. Using Maritech Eye™, seafood companies can now run objective, automated quality inspection of red and white fish at industrial speed. As part of DigiFoods, this system has been fully implemented at Lerøy Aurora measuring fat content, colour, blood, and melanin spots in salmon fillets. In the coming period we aim to combine these measurements with production data to gain new insight and to improve processes. In collaboration with Lerøy Norway Seafoods a solution for whitefish fillets has been developed identifying blood spots, parasites, and skin/fin remnants. This solution is now in commercial use at Samherji in Akureyri, Iceland. Another large ongoing activity for Maritech in DigiFoods is to identify more robust illumination systems that do not rely on halogen lamps. Two new prototypes have been designed by Norsk Elektro Optikk and will be tested in the coming period. Our key persons contributing in DigiFoods are Project Manager Silje Ottestad, System Developer Håvard Løvik and R&D Manager Hardware Jan Rune Herheim.

Intelecy is an innovative SaaS company with a clear goal of enabling sustainable production within the industry. Intelecy's no-code Industrial AI platform is built for industrial data and made for industrial citizens. The easy-to-use tools enable engineers and operators to create, use and operationalize sophisticated AI algorithms without prior coding knowledge. By using Intelecy, a wide range of industrial companies improve resource utilization, prevent unplanned downtime, increase capacity, and minimize their environmental impact. The food processing industry faces a significant challenge in monitoring and ensuring product quality due to the high variability in raw materials. Traditional methods, such as lab testing, can be time-consuming and produce results only several hours after production. The DigiFoods project aims to address this issue using the Intelecy no-code industrial AI platform. The technology analyzes data to provide real-time predictions and helps to maintain quality and efficiency in the face of raw material variability. DigiFoods is a platform for Intelecy to expand its knowledge and test machine learning algorithms against conventional approaches. The Intelecy key personnel contributing to DigiFoods are Senior Machine Learning Engineer Harald Husum and Founder and CTO Bertil Helseth.



• Photo/cc: Vilde Vraalstad, SINTEF

Clipfish samples (thin slices covered in nail polish), used for measuring bulk optical properties. The varying scattering properties cause a striking variation in colour and structure, and will equally affect our spectroscopic measurements.

Article

The robot sorts the salmon based on quality

by Wenche Aale Hægermark, Nofima

The robot is equipped with "eyes" that assess the quality of the salmon. This allows it to sort out the best fillets

The biggest challenge in deploying robots at the fillet factory is space constraints.

"Space limitations are a key factor. The processing line has very little room, so it requires a compact and efficient solution," explains Antonio Candea Leite.

Michael Angelo Amith Fenelon (foreground) working with test equipment at the Lerøy factory in Skjervøy.

Robot with a Sensor

Leite is an associate professor at NMBU, where he leads the RoboSense team in SFI DigiFoods. Together with postdoctoral researcher Abhaya Pal Singh and research engineer Michael Angelo Amith Fenelon, he is developing better robotic solutions for the factory's production line.

Their approach is to combine sensors with robots. "Many sensors available on the market today would require manual operation by industry operators to scan the salmon. Robots can move much more efficiently and precisely. For humans, this is heavy and strenuous work. Robots, on the other hand, can work 24 hours a day without complaining," Leite notes.

Tight and Humid Conditions

The researchers have visited Lerøy Aurora in Skjervøy to see how robots can be used in a real industrial setting.

"This way, we can see how the industry operates. Our goal is to

"Our goal is to examine how the RoboSense concept can be integrated into the factory's operations"
Abhaya Pal Singh, postdoctoral researcher, Nofima


Photo/cc: Abhaya Pal Singh , NMBU

examine how the RoboSense concept can be integrated into the factory's operations," says Abhaya Pal Singh.

He points out that in addition to the tight space in a fillet factory, the environment is also humid. This means that developing new technology is not enough – it must also withstand the conditions in which it operates.

Checking Quality

"Our goal is to integrate a sensor into the robot arm. It can be any type of sensor, but in our case, we are using a Raman sensor," says Michael Angelo Amith Fenelon.

This type of sensor uses spectroscopy – analyzing colors and chemical composition.

Initially, the researchers are using the a Raman sensor to determine the Omega-3 content in salmon fillets.

"If the sensor becomes part of the factory's production line, we can grade the fish based on quality. The challenge is that we must scan a specific area of the fish," explains Fenelon.

The sensor must locate the belly of the fish, where the Omega-3 content is highest, while the fish moves rapidly along the conveyor belt.

Detecting Spots

"We integrate a camera with artificial intelligence models that identify the belly. Then, the robot starts its work. It moves down to the fish and follows the belly without touching it. While doing so, it records a spectrum that can be used to sort the fillet by quality," says Leite.

So far, the researchers have used AI models to detect melanin spots – the black spots in salmon fillets that cause significant losses in the aquaculture industry. "These spots are not harmful, and they do not make the fillets inedible, but consumers do not want them," he states.

Needs to Be Faster

The main challenge now is that the conveyor belt moves too fast. The salmon fillets can travel through the production line at a speed of 40 centimeters per second. "Our solution can handle 20 centimeters per second. Other robots can move very quickly, but we still have some work to do to reach that level," says Antonio Candea Leite.

Next step, the researchers will use the robot to scan around 1,000 salmon fillets at NMBU. They will then compare the quality of the scan results with those obtained manually by a human operator. "This will be our first real test," he states.

Currently, an operator must manually start the Raman sensor. The goal is to fully integrate it into the robotic system so that it operates independently and automatically. The ultimate objective is to refine the solution to a point where it can be practically implemented in the industry.

4. Scientific activities and results

Pillar 1 Novel sensor systems and application development

In this Pillar, we focus on the development of new sensor systems that will enable inline measurement of food quality features. We explore solutions that are based on high-resolution spectroscopy, imaging sensors and low-powered spectral sensors. There are several industrial partners in DigiFoods that are at the forefront of developing in-line food measurement technology. In 2024, we focussed on the development of online applications using hyperspectral imaging, NIR, FTIR, Raman and IR, with involvement from technology providers such as Maritech, NEO, MarqMetrix, Nanoplus and OptoPrecision. Much of the activity has been moving the developed prototypes into the field for real-world testing, as part of Pillar 3.

Another activity in Pillar 1 is the exploration of new opportunities. In 2024, this included activities such as workshops, arranging The Sensor Decade 2024 conference with high profile political attendees, including Karianne O. Tung (Minister of Digitalisation), and international participation, with the aim to increase the visibility of sensor technology developed in Norway and strengthening ties between those that deliver enabling sensor technologies. We also continued our work for developing a strategy for the EU research programmes, contributing to the Photonics call text as part of the Extended Executive Board.

Pillar 1 is led by Marion O'Farrell at SINTEF Digital. Key end-user industrial partners in this Pillar include Lerøy Aurora, Lerøy Norway Seafoods, Lerøy Havfisk, Nortura, Norilia, Biomega and TINE.

FTIR

FTIR spectroscopy is a technique that generates highly resolved, information-rich spectra. One of the intriguing aspects of FTIR is the possibility for characterisation of proteins, not only protein content, but also protein quality, like for instance protein structure, peptide size distribution, and even protein composition. Since water very efficiently absorbs infrared light, FTIR spectra of aqueous samples (like in food-based products) will often be dominated by water absorption. Dry film analysis, on the other hand, has proven to increase sensitivity towards specific analytes compared to the direct analysis of liquids. Dry film FTIR analysis is therefore particularly interesting related to protein characterization, since multiple protein-related infrared absorbances could be "buried" when water is present in the sample.

An important application of dry film FTIR is the characterisation of protein hydrolysates. We have shown that dry film FTIR can be used as an analytical tool to characterise products from industrial EPH processes both at Bioco and Biomega. In a large-scale designed experiment, frequent product sampling from the Bioco process with controlled variations in raw material composition and process parameters were performed. In six weeks, 463 protein hydrolysate samples were obtained and measured with dry film FTIR spectroscopy. In the same period, systematic variations in process parameters such as raw material composition, enzyme type, and water addition, were performed. The FTIR fingerprints were subsequently successfully used to predict average molecular weights, low molecular weight constituents and collagen content, thereby giving

Dry film FTIR spectroscopy also opens the possibility for protein characterisation of other food matrices, such as milk

valuable information on the process. In 2024, this study was published in the journal Food Control. Moreover, work was initiated to build equally robust calibrations for protein hydrolysate characterization of products from the Biomega factory. These results were also positive, and work on these products continues.

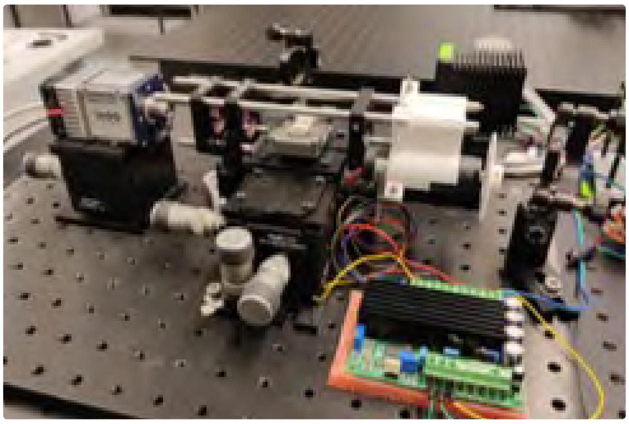
Dry film FTIR spectroscopy also opens the possibility for protein characterisation of other food matrices, such as milk. We have explored the possibility of using FTIR spectroscopy for quantification of protein fractions. For these studies, protein variation has been induced in two ways: through proteolytic degradation during storage of milk, and through cow disease detection (since certain diseases, like Mastitis, induce changes in the protein composition of milk). In both cases the results show that FTIR can quantitatively register minor changes in the protein composition. This application has potential use both on farms (e.g., disease detection) and in process (e.g., cheese making), and the results are expected to be published during 2025.

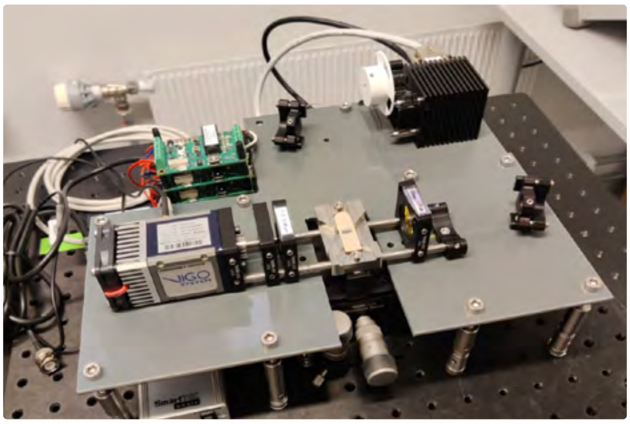
A milestone of the projects was achieved in the successful development of a portable FTIR system for dry film measurements that can be used close to industrial process lines, enabling industrially relevant measurements. This is a technological solution that is currently not commercially available. A characterisation of the system developed as well as an evaluation of its performance in laboratory and industrial environments, respectively, was published in the journal Analytical Methods in 2024. Another important work that was started simultaneously,

Photo/cc: Ulrike Böcker, Nofima

Dr. Bijay Kafle and Dr. Per Waaben Hansen having a lively discussion during the PhD defence.

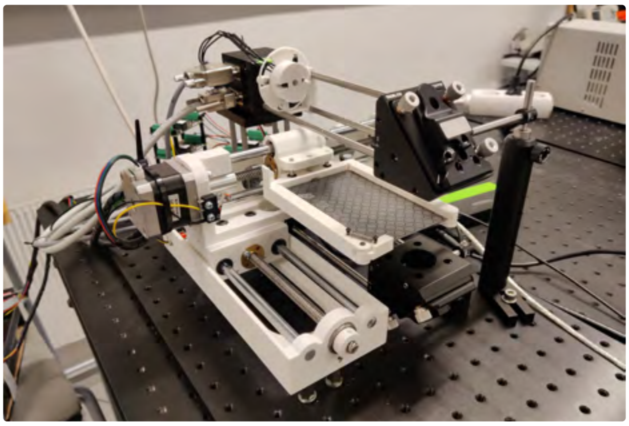
was a study on the transferability of calibrations from our benchtop dry film FTIR systems to the portable FTIR system. Calibration transfer to the portable system will simplify and be an economically feasible way of developing industrial applications, and results so far suggest that this is feasible for diverse matrices such as protein hydrolysates, cell media and microorganisms. There are now several feasible future directions in the further development of the portable system:



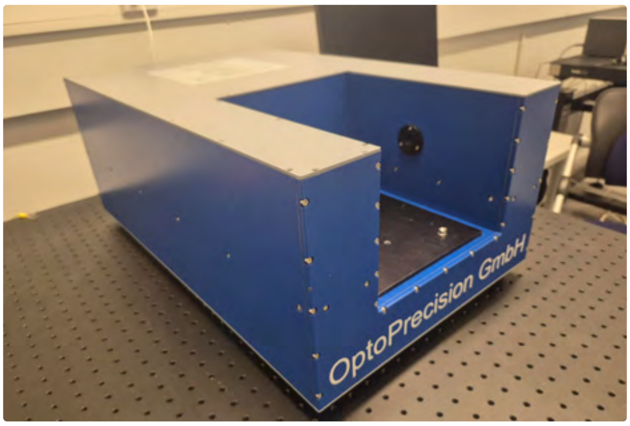


Photos/cc: Pranish Karki, NMBU

To the left is the prototype with an optical waveguide for liquid measurements.
The setup to the right is the portable version being developed for the on-line measurements.



Photo/cc: Pranish Karki, NMBU



Photo/cc: Mehmet Can Erdem, NMBU

The prototype to the left is designed for dry-film measurements. To the right, the OptoPrecision Liquid Monitor (LIMO) device is utilized for the transmission measurements.

1. using the portable system for manual process understanding and process development in industrial environments; and
2. using the portable system as part of an inline system with the adaption of automation and robotic sample handling for automatic sampling from process streams. Both concepts are now being followed up.

A final milestone in the project was achieved with the successful PhD dissertation of Dr. Bijay Kafle. The PhD defence was a very interesting day with lots of good discussions on spectroscopy and food analysis, first if all due to the efforts of the candidate and the two opponents, namely Dr. Per Waaben Hansen (Foss Analytical and University of Copenhagen) and Prof. Eva Falch (NTNU).

Handheld and portable IR

The BioSpec group, in collaboration with the University of Ulm, and industrial partners nanoplus and OptoPrecision, has been working towards the development and application of innovative handheld and portable infrared devices for quality measurements of food. Significant strides have been made since the last reporting period, and the project is now in an advanced stage.

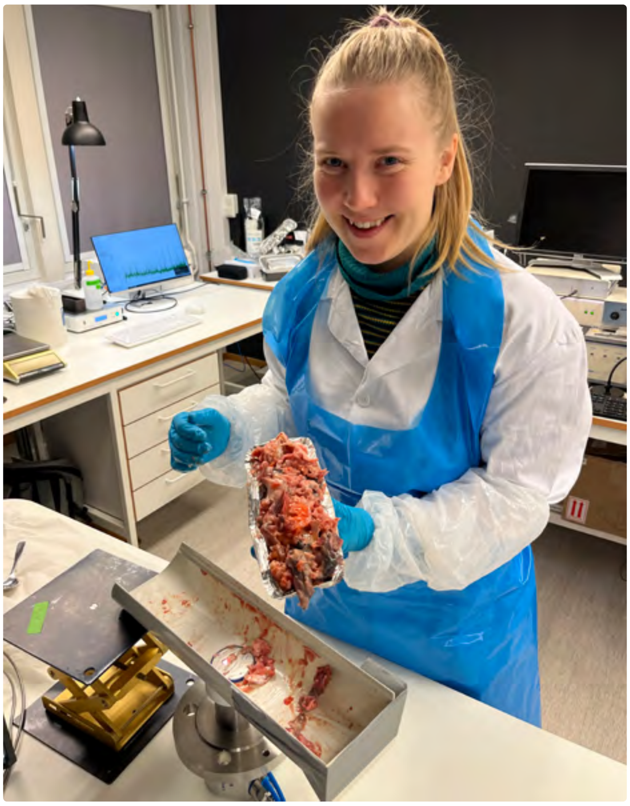
We have successfully established three prototypes for portable instruments at NMBU. Two of these prototypes are based on a novel tunable laser developed by our industry partner, nanoplus. This laser is uniquely tunable in the protein range, thereby enhancing our ability to accurately analyze food samples. The two prototypes differ in terms

Overall, our project has made significant progress in the development of novel infrared devices for food quality measurements

of their sample interaction mechanism. The first prototype is designed to measure samples in liquid form on the surface of a waveguide. The second prototype is engineered to analyze dried film samples. Pre-industrial versions of both prototypes are currently under development and will soon be tested for protein quality measurement in collaboration with the project partner, Biomega. The third prototype has been developed by OptoPrecision. This prototype is designed for transmission measurements of liquids, and it has shown promising results so far. We are also evaluating different single-wavelength emitting lasers, customized for specific applications. These lasers are expected to further enhance the functionality and versatility of our infrared devices.

In the next phase of the project, we plan to conduct extensive testing of the devices with industry-relevant samples. We aim to work closely with food and feed producers to ensure that our devices meet their needs and expectations. In addition, we will continue our collaboration with the FTIR project, exchanging samples from Bioco and Biomega. The goal is to determine different process parameters using both the FTIR system for dry film measurements and the tunable laser-based IR system.

Overall, our project has made significant progress in the development of novel infrared devices for food quality measurements. We look forward to further testing and refinement of our prototypes, and ultimately, their application in the food industry.



Photo/cc: Jens Petter Wold, Nofima

Tiril Aurora Lintvedt during calibration of Raman and NIR instruments for monitoring of salmon by-product composition.

RAMAN

The project RAMAN is studying how Raman spectroscopy can measure quality parameters such as fatty acid and protein composition in different foods. The focus of the project is on novel sampling strategies and the use of state-of-the-art technology to reduce sampling time and make Raman suitable for process measurements.

During the first four years we have evaluated Raman for rapid and non-contact assessment of fatty acid features (EPA+DHA) in intact salmon fillets and in-line continuous monitoring of fat, protein, collagen and bone in the poultry rest raw material entering the process of enzymatic hydrolysis at Bioco. We have used a non-focused stand-off probe from MarqMetrix that enables scanning of heterogeneous foods and streams, and this approach seems very feasible. High quality spectra can be collected in seconds. This work was the basis for the PhD thesis of Tiril Aurora Lintvedt.

In 2024 we concentrated on three interesting topics:

1. When using Raman stand-off probes, the distance between instrument and sample can vary. This will often require some kind of spectral pre-processing. We have done systematic experiments to elucidate how such processing can be done in the best possible way with the aim of developing a protocol for efficient pre-processing of in-line Raman spectroscopy.

2. NIR spectroscopy is well established as an in-line method in the food industry. It is therefore interesting and important to benchmark Raman against NIR and outline the pros and cons with the two methods. We will soon publish a study that indicates that Raman is more robust towards varying sample texture/structure compared to NIR. At least, much simpler calibrations can be obtained. This is an important aspect to consider when choosing the method to use for a certain application.

3. We will compare Raman and NIR side by side in an industrial food process in 2025. We spent quite some time in the lab at Nofima to calibrate the two systems so that they are ready to be installed and evaluated. This is the first time we are using Raman (and NIR) as contact probes which will be installed and measure inside pipes. We are excited about this! In this context, we have also spent time on developing a robust in-line setup of the two instruments, so that they can stay in the industry under cold/warm/wet conditions, for long term evaluation and comparison.

The work has so far been a collaboration between MarqMetrix, AspenTech, Norilia, Lerøy Aurora, Biomega Group and Nofima.

HYPERSPEC

The HYPERSPEC project has investigated the use of hyperspectral imaging for detection of blood and melanin spots in salmon fillets, which is one of the most important quality issues faced by the industry since these spots can have a relatively high prevalence and large impact on product value, in some productions. We developed an improved and promising approach based on neural network classification of hyperspectral image data. In 2024, we summarized the progress from this work in the form of a full-length scientific publication, that has been accepted and published in Aquaculture.

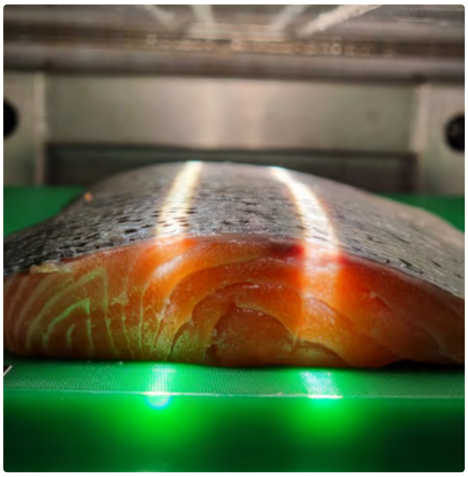
In the framework of DigiFoods, together with additional funding from an FHF project, Nofima and Maritech developed a solution for detecting nematodes in cod fillets. This work was motivated by the limitations of traditional methods for detecting parasites in fish, specifically manual inspection on candling tables, which are slow, labor-intensive, and only detect about 50 % of parasites. The proposed method improves parasite detection rates to 73 % using deep neural networks and hyperspectral imaging data. The hyperspectral data acquisition was performed in Portugal under industrial conditions. This solution is currently integrated as a quality parameter in the Maritech Eye. The technology can be directly incorporated into existing industrial processing lines, allowing for real-time detection of nematodes in fish fillets. The work was recently published in Scientific Reports, titled "Hyperspectral imaging and deep learning for parasite detection in white fish under industrial conditions." Currently, there is a DigiFoods spin-off project funded by FHF, where Nofima, NMBU, Maritech, Lerøy, and Marel are investigating possible solutions for the automatic removal of nematodes based on the detection provided by this method.

In the HYPERSPEC project, we have utilized information from hyperspectral images captured with interactance illumination to determine various quality parameters in seafood. These quality parameters can be assessed even without precise information about the depth of light penetration in fish muscle. However, a more detailed

(Photo to the left) Hyperspectral imaging of cherry tomatoes in order to estimate their sweetness, while remaining compatible with in-line, non-contact and high-throughput measurement. *(Middle)* Karen Wahlstrøm Sanden measuring a cod fillet on a green polyethylene background with the SmartSensor, aiming to better understand the light penetration through the sample with interactance mode imaging. *(Right)* A salmon fillet with the skin side up being imaged by the MaritechEye which takes an image between the two parallel light lines that illuminate the sample in an "interactance" mode of illumination.

Photo/cc: Lars Gidskehaug, NEO


Photo/cc: Samuel Ortega, Nofima


Photo/cc: Roean Romeyn, Nofima

characterisation of light penetration depth in fish tissue could provide additional valuable insights. To explore this, in 2024, we collected a large dataset aiming to quantify the depth of light penetration in fish muscle for both salmon and cod, considering samples with and without skin and using for the background different substrate materials that exhibit varying spectral contrast with the muscle (see image above). We employed the Maritech Eye to capture hyperspectral images, the SmartSensor for point measurements at different interaction distances and a laser height profiler to measure the thickness of the samples. A significant challenge in this dataset is the need to co-register various multimodal datasets, including hyperspectral images, RGB reference images, and 3D laser scans. Ongoing work is to complete the processing of the dataset and draw inferences on the interactance mode light penetration for different types of fish samples. This study is expected to improve our understanding of light penetration within fish muscle.

To process the hyperspectral data in real time on the production lines we use the software Breeze from Prediktera. All new functionalities must be developed and implemented in Breeze to be able to apply them online. This year we have worked on a new solution to detect body regions based on fillet shape profile. This allows more detailed reporting of where the defects occur. It also makes it possible to identify the Norwegian Quality Cut (NQC) in salmon fillets independently of orientation. In addition, we have together with Prediktera developed a new methodology to automatically compensate for conveyor belt speed and frame period to be able to measure accurate sample dimensions in compressed images independently of sample orientation.

NEO has been developing two imaging solutions for Maritech Eye: One is an LED-based alternative, and the other is an enhanced version of the current halogen solution. Both options feature new front optics that provide a sharper illumination line and minimize stray light.

A set-up based on NEOs camera has been designed and tested for in-line assessment of sweetness in cherry tomatoes. This has been a collaboration with Nofima, where this HSI solution has been compared with non-contact interactance measurements (SmartSensor). The set-up was successfully tested at the packing line at Wiig Gartneri. The aim of this application is to be able to sort out tomatoes that are not sweet enough.


Photo/cc: Karen W. Sanden, Nofima

Vilde doing Clipfish measurements in the lab, before traveling to Belgium with fish in her suitcase!

NIR

In the NIR project, we have continued testing and further developing our NIR prototypes for fundamental research by our PhD student, Vilde Vraalstad, and for industrial trials that secure the innovation potential of our work. The work here is also relevant for our spin-out commercialisation project, SenseInside, where we have a new prototype built using the same core technology.

To better understand how our water content prediction models work so that industrial measurements are more robust, Vilde conducted a study of bulk optical properties of dried salt-cured cod (clipfish), in collaboration with KU Leuven in Belgium. Twenty clipfish were measured with our NIR prototypes (SmartSensor and MiniSmartSensor) at Nofima and then transported in Vilde's luggage to Leuven for measurements in a double integrating sphere setup. To achieve the necessary thin and smooth sample slices of clipfish, a custom-built device was developed specifically for this purpose during the study. The measurements were used to quantify the bulk optical properties of fish with varying water content, understand how this affects the light propagation through the fish, and investigate the effect these have on our NIR interactance measurements. We have obtained increased understanding of our spectral measurements and are better suited to achieve more robust measurements of clipfish and other complex, highly scattering food products. This work will be published in 2025.

We also conducted controlled preliminary measurements of tomatoes in the lab. Vilde Vraalstad and our summer student Bård Pedersen brought our miniaturised NIR interactance based sensor (FragoPro) and took part in a measurement campaign with 200 cherry tomatoes, together with Nofima and NEO. This work will be continued in 2025, where we investigate how various real-world disturbances affect our instrument performance.

Vilde presented our work at various conferences and meetings around Europe in 2024

- Norwegian electro-optics meeting (Oscarsborg, May 2024), with the title "Many spectrometer users; not enough instrument knowledge".
- SensorFINT conference (Cordoba, Spain, May 2024), with the title "Get to know your spectrometer, and how it compares to other spectrometers on the market".
- FOSS Food analytics conference (Copenhagen, November 2024), with the title "How a fundamental understanding of spectroscopic sensors makes more robust solutions for real-world applications"
- Our first-principles approach for robust measurements in real-world applications was also presented at the PHOTONFOOD, DigiFoods and FoodSafeR Joint Symposium (Vienna, November 2024).

We have also seen that sugar predictions with NIR correlate strongly with sensory measured sweetness, assessed with the sensory panel at Nofima

Photo/cc: Emil Nørgaard, Velkendt

Vilde presenting our work at the Foss Food Analytics conference.

During 2024 we tested a calibration for sugar estimation in cherry tomatoes based on the SmartSensor. It was tested on five independent sample sets harvested from February to November, more than 1000 tomatoes. Testing was done on single tomatoes in the lab, on tomatoes in movement and finally on entire tomato trusses moving on a conveyor belt at Wiig Gartneri.

The instrument works very well and produces stable results with low prediction errors. We have also seen that sugar predictions with NIR correlate strongly with sensory measured sweetness, assessed with the sensory panel at Nofima. These results have been published in Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy.

Photo/cc: Sissel Beate Rønning, Nofima

Marion presenting digitalisation at the ReThink Food Technology conference 2024.

Photo/cc: Killian Munch, Playroom

The Sensor Decade 2024.

OPPORTUNITIES

This is a small project that centres on creating new opportunities and managing new ideas.

In 2024 we conducted several activities related to this project.

- In April 2024, DigiFoods hosted a European a technical and networking event in collaboration with EPIC called Photonics for AgriFood Industry – Enlightening the Future at DigiFoods, with the aim to explore innovative applications of photonics technologies in various aspects of agriculture and food production. epic-photonics.com. You can read more about this event under Chapter 7.

- We set-up three summer internships (Bastian Krogh, Bård Pedersen and Jonas Vistad) at SINTEF as part of DigiFoods, and they worked on the FragoPro sensor platform for MOBILESENSE and the SenseInside sensor prototype, which is also being explored in the spin out commercialisation project SenseInside. Bastian and Bård will each do a Masters internship and Masters project, respectively, at SINTEF in 2025. Jonas, who goes to secondary school will continue in a year-long placement programme (1 day a week) in autumn 2024 and spring 2025.

- NMBU, SINTEF and Nofima developed a new concept around sample handling for dry-film FTIR, and this has resulted in a commercialisation proposal, RABBIT, which was sent in autumn 2024, and we will get an answer early 2025.

- Marion O'Farrell continued on the Executive Board representing the Food and Agri working group in Photonics 21, contributing to upcoming call text within photonics and spectroscopy. We also provided further input to the Strategic Research and Innovation Agenda (SRIA).

- Marion O'Farrell attended the technology conference for ReThink Food in June 2024, which focused on the digitalization of future food systems in Norway.

- Marion presented how digitalization contributes to reducing food waste at SINTEF Digitals yearly digitalization event, Digital Fremtid digitalfremtid.net.

The Sensor Decade 2024 was held 5–6th June 2024, as part of Oslo Science City Arena, with 283 participants sensordecade.com. It took place at the University of Oslo and Marion O'Farrell (SINTEF), who leads pillar 1 in SFI DigiFoods, led the organization of the conference. To involve students, we also have The Student Expo, led by Startup Lab and the winner of Best Student Organization went to **Helix** from NMBU – Norwegian University of Life Sciences. The conference is partially support by NFR, Oslo Kommune and 3 cash-contributing industrial partners – Sony Norge, Kongsberg Discovery and Tomra ASA.

Pillar 2 Robot and sensor integration

In today's rapidly evolving food industry, the integration of advanced technologies is revolutionizing production processes. The flourishing field of Agri-Tech has highlighted the critical role of automation and advanced sensing systems in enhancing efficiency and precision across both outdoor farms and indoor facilities.

Our research focuses on leveraging robotic systems to optimize sensor deployment. By precisely positioning sensors, we aim to maximize the accuracy and relevance of data collection, ensuring that every measurement contributes meaningfully to the production process.

Conversely, we're exploring how sensor data can be harnessed to refine robotic operations. This bidirectional relationship between robots and sensors promises to elevate decision-making processes and overall system performance, paving the way for truly intelligent agricultural solutions. Looking ahead, our goals include:

1. Developing fully autonomous robotic systems
2. Creating automated sample preparation protocols
3. Enabling real-time analysis of complex food products through smart sensor integration

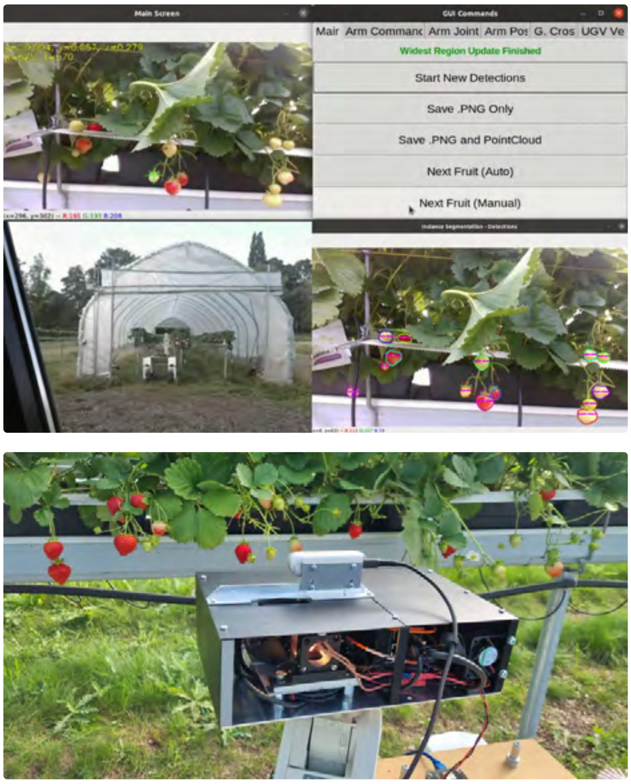
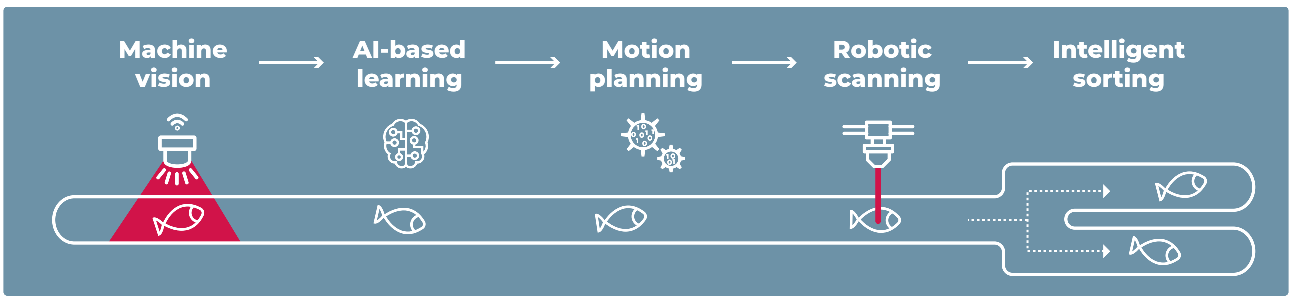


Illustration of the graphical user interface developed (top) for use during field deployments and the robotic arm pointing (bottom) the sensor at the strawberry for sugar content data capture.

In the long term, we envision pioneering high-throughput spectral analysis techniques for biological samples using cutting-edge technologies like FTR and Raman spectroscopy. This ambitious vision aligns closely with ongoing research across our other pillars, promising a comprehensive advancement in food science and technology.



The overall process of using in-line sensor technology handled by robotic solutions.

Photo/cc: Antonio Candea Leite, NMBU


ROBOSENSE's latest activities: Michael and Abhaya visited Nofima Tromsø to brainstorm on using Maritech Eye; Michael and Abhaya collecting videos and images of the fish fillets in the Lerøo Aurora, Skjerevøy plant.

ROBOSENSE

ROBOSENSE enables the robotic operation of intelligent sensors in industrial food processes, providing accurate and effective in-line measurements of relevant parameters in heterogeneous foods. The project aims to:

1. identify optimal methods for collecting spectral measurements from specific regions of complex food samples moving on a conveyor belt;
2. develop an innovative and cost-effective concept for robotically controlled measurements;
3. design and develop a robotic prototype for testing under realistic conditions expected in a food processing facility.

In 2024, the ROBOSENSE team successfully achieved the following goals and objectives:

1. Daniel Glemminge and Abhaya Pal Singh joined the team as a master's student and a postdoctoral fellow, respectively, to conduct R&D activities for implementing and testing the minimum viable product (MVP) concept of a robotic Raman spectroscopy system in a salmon fillet processing line;
2. Conclusion of the Master's thesis titled *Potential Field-Based Path Planning for Enhanced Sensor Coverage in Robotic Salmon Inspection* by Daniel Glemminge;
3. A new image and video dataset of salmon fillets, collected at Lerøy Aurora, Skjervøy, featuring variations in color, shape, trim, melanin, and blood spots, designed for use as input in an AI-based image processing algorithm within the robotic Raman spectroscopy pipeline;
4. A journal article in manuscript form on *RoboSkanLaks, a path-planning algorithm for the robotic scanning of salmon fillets in the presence of melanin spots while avoiding the local minima case*, along with another article on dataset collection, analysis, and experiments;
5. Development of a pilot-scale system concept for robotic in-line scanning under relevant operational conditions in the food processing industry;
6. Visited Nofima in Tromsø to discuss the use of Maritech Eye technology in the spin-off project Kveis-trim;
7. Poster presentation on Robotic Raman Sensor Integration for Assessing Omega-3 Fatty Acid Content in Salmon Fillets at the Advancements in Monitoring Food Contamination and Quality Symposium, held on 27–28 November 2024 in Tulln, Austria, organized by PHOTONFOOD in collaboration with DigiFoods and FoodSafeR.

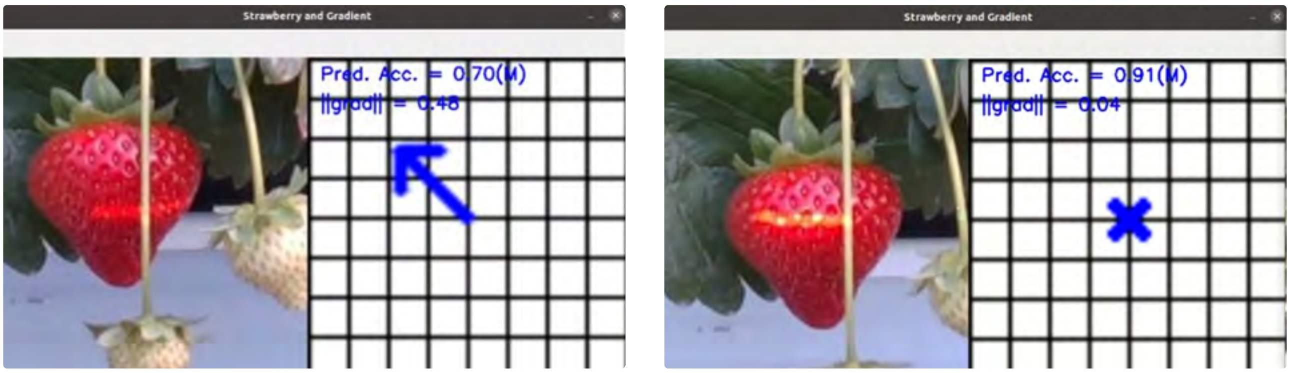
In 2025, the ROBOSENSE team plans to conduct its first demonstration of an experimental trial on scanning salmon fillets to measure Omega-3 fatty acid content using a fully integrated, automatically triggered Raman probe mounted on a robotic arm and equipped with the proposed melanin-spot-free path-planning algorithm. The next steps for the ROBOSENSE team in 2025 include:

1. Enhancing the robotic Raman sensor scanning process in terms of speed and accuracy;
2. Writing and submitting 1–2 research articles based on collected datasets and novel experiments;
3. Validating the pilot-scale system and MVP concept for robotic in-line scanning under relevant operating conditions, in collaboration with the RAMAN project and industry partners;
4. Developing a *Digital Twin concept* for ROBOSENSE – a virtual replica of a fish processing line with a conveyor system – enabling the generation of virtual salmon fillets, deployment of cameras and robotic arms, testing of AI-based image processing and motion planning algorithms, and real-time simulation of salmon scanning, ultimately extending the robotic system's lifespan and reducing logistics costs.

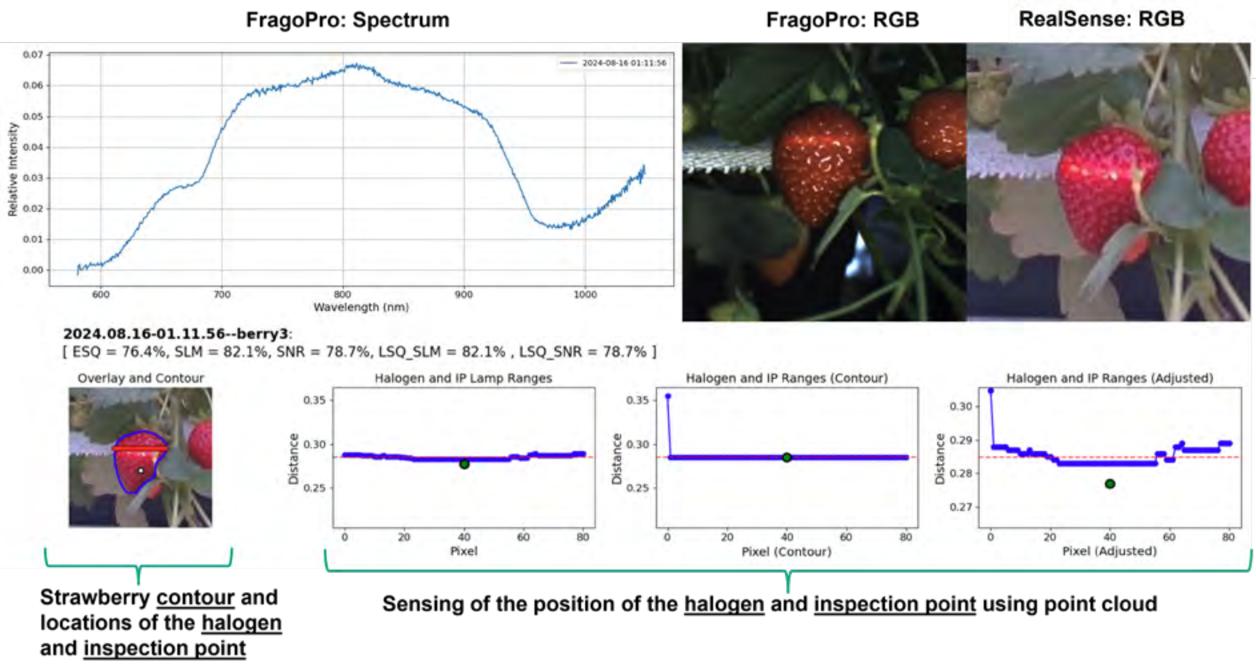
MOBILESENSE

In MobileSense, we continue with the configuration of the mobile manipulator designed, incorporating the mobile robot platform (Thorvald from Saga Robotics) equipped with the robotic arm (Mitsubishi) for sensor positioning, the stereo camera (RealSense), and the LiDAR (Ouster) for autonomous navigation. The system also includes the sensing technology (FragoPro) developed by the project partners at SINTEF, which is used for estimating sugar content in strawberries.

In 2024, we enhanced our intelligent system, improving its ability to locate strawberries and their experimentally ideal regions, as well as to autonomously position the sensor for spectral data collection. Furthermore, we proposed a method of visual servoing aiming to adjust the sensor position, optimizing signal quality during capture. At this stage, FragoPro was not used, instead, a signal quality methodology based on an expected signal quality function was employed, designed to capture the sensor's alignment with the fruit and account for potential occlusions. We trained the proposed method with data from both a simulated and a real environment, achieving promising results, with the next step being the validation of the model using spectral data.



Example of the proposed model pointing away from the occlusion (stem) and then repositioning the sensor to enhance spectral data capture.



In late summer of 2024, we utilized an improved version of the FragoPro sensor, operated by the robotic arm, to autonomously collect spectral data from strawberries. We conducted successful tests on the intelligent system for autonomous sensor positioning on the mobile manipulator, which ensured accurate spectral data capture according to SINTEF's specifications. We also collected combined data from the FragoPro and the mobile manipulator for further training of our novel visual servoing solution, this time using data derived from the spectrum, and to allow SINTEF to analyze the impact of sensor positioning on signal quality. These experiments were carried out using a graphical user interface (GUI) developed to be used in coordination with the FragoPro's GUI, allowing manual synchronization between the two systems.

For 2025, the synchronized data has been shared with SINTEF, and the training of the visual servoing model has been done. Currently, we are verifying the efficacy of this model, which incorporates data derived from the spectra, as part of the final validation for a journal paper set to be submitted in Q1 of 2025. Furthermore, we are considering splitting the paper into two publications: one detailing the data acquisition method and the data itself for conference proceedings, and the other focusing on the proposed model for a journal submission.

Since the positioning procedure has already been executed and validated, the focus will now be on the autonomous navigation and planning for the synchronized use of the mobile base with the robotic arm. Last but not least, we will be implementing closed-loop control that uses feedback from FragoPro during the spectral data acquisition, which will be of utmost importance in optimizing the capture of spectral data and the final autonomy of the entire system. These developments will be documented in at least two future papers, presenting our findings and advancements.

on first, to develop and implement deep learning solutions for individual fruit detection and segmentation and second, to design a machine-learning-based solution for optimal placement of the sensor in front of the targeted fruit to maximize accuracy and robustness.

A field test of FragoPro mounted on Thorvald was executed in late summer. The test used manual, open-loop robot control. In this way, the team gained operational experience with the features and limitations of the robotic platform. Sensor data from the test was analyzed at SINTEF, revealing several opportunities for improved design.

In 2024, the project aims to carry out a closed-loop field test, demonstrating improved sensor performance with autonomous robotic positioning.

Pillar 3 Integrated in-line sensing solutions

When a food sensor has been developed in a controlled environment, there is still a long journey to industrial implementation. Several commercial food sensors have failed because they were not robust towards the inherent bio-variability encountered in the processes and products. Thus, strategies that address the practical and theoretical considerations for sensor implementation are clearly needed for the instruments that are already used commercially, but also for techniques for which we have very limited industrial experience, such as FTIR, Raman and fluorescence spectroscopy.

In Pillar 3 we are developing and validating efficient solutions and strategies for successful sensor implementation in food production. In other words: We are making the sensors actually work in the food companies. In DigiFoods, implemented sensors are also be used to explore and map variation in food processes over time. The sensors developed in DigiFoods are now providing previously unavailable information from food processes. This has for instance been shown by industrial use of Raman and FTIR sensors in 2024. Moreover, calibration robustness and calibration transfer are important aspects of all sensors developed in Pillar 1. Thus, for 2025, a new project, TRANSFER, will start, emphasising the importance of these aspects.

Pillar 3 is led by Dr. Nils Kristian Afseth at Nofima. For 2024, key partners in this Pillar have included all food partners, NEO, AspenTech, MarqMetrix, Idletechs, SINTEF, NMBU and Nofima.

ROBUST

A major bottleneck for industrial sensor implementation is to get from the measured signal to reliable estimates of food quality attributes. A robust calibration model needs to handle chemical and physical sample variations as well as harsh and changing surroundings. Spectroscopic sensor technology has many application areas in in-line food quality analysis. Some applications are well established, and robust calibration models can be purchased from instrument vendors. New or less standardised applications require development of new calibration models, which can be a time consuming and expensive task. Also, it is necessary to maintain models over time for both instrumental, environmental and process reasons.

In 2024 work in ROBUST has continued along several axes and one important one has been building an industrial dataset at Hoff for the French fries production line – both spectroscopic quality measurements and process control parameters – as a testbed for several DigiFoods projects. We now have a collected dataset covering most of 2024. This will allow for practical testing of methods for calibration model maintenance and robustifying these to changing conditions. The test data will also allow for investigating connections between quality measurements and the control of the production process. We hope that this work will produce interesting findings in 2025 for Hoff in particular, but also to others.

Another axis has been initial testing of calibration models for core temperature in fish cakes at Lerøy's facilities at Stamsund in Lofoten. This is a continuation of work already initiated in previous years and which involved Idletechs. Being able to measure core temperature is a of recurrent interest to food production industries as optimally tuning production lines often encounters conflicting considerations: higher temperature for food safety as opposed to lower temperature for reduced loss of moisture and hence higher perceived quality of food.

One aspect of the ROBUST project has been investigation into calibration transfer techniques which addresses the questions of how to build a calibration on a new device (repair, new acquisition) given that one already exists for a similar device. Techniques for solving this problem sometimes work with transferring a model built in the laboratory to an industrial environment or maintaining models over time. While many methods have been proposed, little work has compared them or specified when any given model is expected to work better than others. A scientific article is expected in 2025 summarizing this work.

Bioco and Biomega have been active partners in pursuing techniques for monitoring their production processes and involving spectroscopic techniques for assessing raw material variations and also for products at different stages of their production line. One development in 2024 has been preparations for the use of new instruments and sampling arrangements where measurements would be done on materials streaming through closed pipes instead of requiring open access to the material stream. This will also allow for pursuing the comparisons between NIR and Raman instrumentation for industrial applications and where the question of robust methods is central. Finally, performance of models will be assessed over time in-/on-line at industry partners with the objective of improving the understanding of industrial processes both in terms of distributions and dynamics, but also in terms of relationships between processing stages. This is a long-term goal which will continue in 2025.

Finally, a note on project definitions and developments in DigiFoods: the project ROBUST has been terminated as of end-of-2024. Its activities will be continued under several of the other projects within DigiFoods, including the new TRANSFER project. The reason for terminating the ROBUST project has primarily been the realization that many of the projects within DigiFoods have an integrated approach to making their work robust and as such it is an activity that is naturally included in many projects.

Photos/cc: Lars Erik Solberg, Nofima

Testing of NIR instrumentation for core temperature measurements at Lerøy, Stamsund. To the left the thermometer is shown and illustrates how core depth was controlled using tape. *(Photo to the right)* The instrument (top left) is shown with a protection against the hot water vapor from the oven (black silicon sheet). The bright spot on a fish cake shows where the NIR instrument does the measurement.

Photo/cc: Jens Petter Wold, Nofima

DigiFoods visiting Nortura's egg facility in Revetal.

EXPLORATION

A key challenge in many food processes is the missing knowledge about the actual quality variations. This information is crucial to gain insight into a given process to understand process behaviour over time. The knowledge about quality variation is usually based on sporadic or systematic measurements, maybe weekly or monthly. Process operators also possess valuable informal process knowledge based on personal experience and insight.

With smart sensors that measure and continuously monitor the critical quality features in a process, it is possible to document and map these variations along the processes and over time. The aim of EXPLORATION is to map exactly this variation and based on the results, figure out potential improvements, either in the final product or in the process itself.

In 2024, the project has included finishing the measurements of fat contents in dry cured sausages, measuring the variation in fatty acid composition in pork pack fat, and starting on measuring the purity of eggshell membranes. The motive for measuring fat in dry-cured sausages is that the fat content affects the quality and shelf-life of the final product, as well and the dry-curing process. At Norturas facility in Sogndal, we measured fat content in about 1500 sausages without interfering in the process, prior to the dry-curing process. This has given insight in the process variation and acted as a validation to a factory upgrade in Sogndal. The work was done in collaboration with the RCN-funded project DigiSpek (NRC no. 327946) and gives very nice synergy effects for both projects. Better control of the fat content will give less variation, better control of the drying process, and increase the yield of the sausages.

The motive for measuring the fatty acid composition in the raw materials is that the fatty acid composition determines the physical properties of the fat, most importantly melting point and viscosity, affecting the shelf-life and processing of the dry-cured sausages. The conclusion of the measurements was that the variation in fatty acid composition at Norturas facility in Tønsberg is already far smaller than what has been observed at other production lines, and that there is little potential gain in trying to reduce it further.

The motive for measuring the purity of eggshell membranes is that Norilia is currently separating eggshell membranes from the eggshells. In doing so, they can sell the eggshell membranes and reduce the waste that the eggshells otherwise represent. By developing a fast spectroscopic method, the separation can be optimized, potentially further improving the sales of eggshell membranes.

Photo/cc: Jens Petter Wold, Nofima

Robotic handling of eggs at Nortura Revetal.

By developing a fast spectroscopic method, the separation can be optimized, potentially further improving the sales of eggshell membranes

Pillar 4 Utilization of large-scale quality assessments

In this Pillar, we develop data-driven solutions for process, product, and value chain optimisation. The solutions are based on extensive food quality measurements, combined with other relevant data sources from farm, industry, and consumer. The solutions will be targeted at three application areas: Farming, food processing, and marketing.

There is a strong link between health and welfare of animals, fish and plants, and the resulting food quality. Decision support for farmers involves for instance optimised feeding, care, and time of harvest, as well as early detection of health and welfare threats. We will combine food quality measurements with data on environmental and husbandry factors to investigate how they affect quality and health. This knowledge can be used in either long-term production planning or in real-time decision support.

In-/on-/at-line food quality measurements can be used to monitor, optimise, and control production processes. We will develop solutions that transform the multitude of measured and registered data in a production line into meaningful information needed to adjust and stabilize the production or tailor-make specific end-product quality categories. As in farming, the information can be used in either long-term improvement work or real-time monitoring and optimisation.

Well-documented and tailored food products can contribute to increased consumer satisfaction and reduce food waste. We will investigate consumers' attitudes and willingness to pay for different quality categories, and from that develop communication and marketing strategies to target different consumer profiles. We will investigate how the growing focus on food waste may impact food choice with respect to product quality.

Pillar 4 has had three projects in 2024; COMBINE, MODEL and CONSUMER. COMBINE and MODEL end in 2024, and results will be applied and developed further in two new projects in 2025, called INSIGHT and OPTIMISE. The CONSUMER project continues in 2025.

Pillar 4 is led by Ingrid Måge at Nofima. Participating partners in 2024 were TINE, Nortura, Norilia, Biomega, Intelecy, Lerøy Aurora, Maritech, NMBU and UPV.

COMBINE

Data preparation is a crucial and resource-demanding part of any data science project, especially when we need to combine data of different types and from different sources. Data preparation includes operations such as cleaning, synchronising, aggregating, transforming, structuring, and validating data.

In previous years, we have developed routines for synchronisation, aggregation, feature extraction and combination of data from different parts of the cheese making process. The most challenging part of this procedure has been to combine so-called Batch and laboratory data with timeseries data from the process historian, and extract meaningful features from the time series that can be combined with the Batch data. This work has been a collaboration between TINE, Nofima and Intelecy, and resulting data sets have been used further in the MODEL project to analyse process variation and identify key process variables. In 2024, we have also had discussions with Lerøy Aurora and Maritech on potential data sources that need to be combined in order to find relations between salmon fillet quality and production parameters. In this case, it will also be necessary to combine batch, or fish group, data with time series from e.g. the sea phase and from inline measurements with Maritech Eye.

All data-driven solutions require some form of data modelling

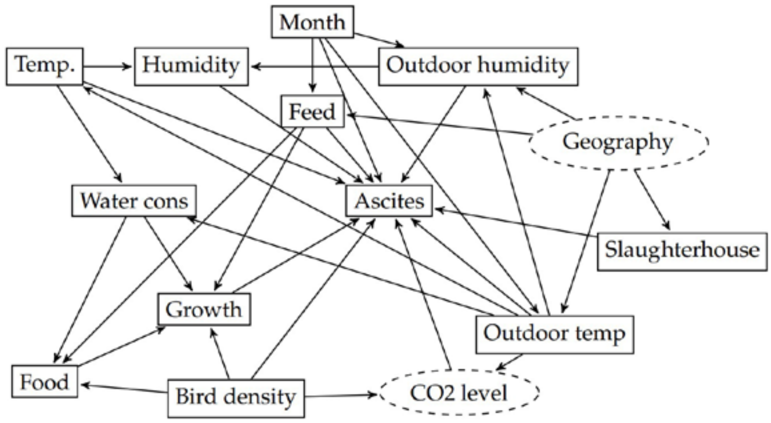
Another topic has been preprocessing of industrial time series for process modelling. PhD Marco Cattaldo has previously compared a broad span of methods for estimating lags between different sensors in a process line and found that the metrics *Distance Correlation and Maximal Information Coefficient* are methods that can be recommended. This recommendation is based on a large simulation study and results from the hydrolysis process at Bioco. The work has been published in Chemometrics and Intelligent Laboratory Systems. This year, Marco has developed a general pipeline for making prediction models based on industrial time-series data, and a strategy for optimising the pipeline. The pipeline includes all steps from raw data to a validated model, including preprocessing of individual timeseries, synchronisation of data from different sensors, and selecting the modelling method. This work is based on data from Bioco and a scientific publication is in preparation.

UPV has developed a new algorithm for smart subsampling of large production databases, called "retrospective design of experiments". In DigiFoods, we will apply and further develop this method. The work is a collaboration between UPV and Nofima, and a plan has been outlined for applying the method to process data collected from the cheese making process at TINE.

MODEL

All data-driven solutions require some form of data modelling. In DigiFoods, the models will typically relate quality attributes to controllable and uncontrollable factors from farming or processing. In MODEL we develop methodology for two types of models: causal modelling and real-time modelling. We also apply different types of modelling methods in processes at industry partners.

Directed Acyclic Graphs (DAGs) is an increasingly popular framework for designing statistical models for estimating causal effects. A causal DAG is a graph consisting of nodes and arrows. The nodes represent variables one can measure, and the arrows indicate how the variables are causally connected. A DAG describes a theory or hypothesis about the system at study and should be based on domain knowledge and previous research results. PhD student Christian B.H. Thorjussen is applying this framework in a case study on chicken production with Nortura, to estimate the causal effect of feed on the health parameter *ascites*. The work has been presented at several conferences and a scientific paper is in preparation. Christian has also developed a simple and flexible machine learning method to test conditional independencies inferred by a DAG. This is an important step in the framework, for validating the DAG and identifying missing arrows. The method has been published in the scientific journal Algorithms. Further work on this framework will be continued in the new project INSIGHT.



Photo/cc: Ingrid Måge

(Figure to the left) The DAG describing causal relationships between chicken production parameters and ascites. *(Photo on the right)* Magne Aase at TINE Jæren demonstrates how data can be visualised and made available to the process operators.

The second type of model is intended for modelling industrial time series. PhD student Marco Cattaldo has proposed a selection of new methods for modelling process dynamics in cases when the data comes from both spectroscopic sensors and other process measurements. The new methods are based on the multiblock method *SO-PLS* and *Dynamic inner PLS (DiPLS)*, and a scientific paper that presents and compare these methods has been published in Journal of Chemometrics.

We have also continued to explore and model process data from TINE, with the aim of understanding more about factors that affect dry matter content in the cheese, in a collaboration between TINE, Intelecy and Nofima. This work has already led to adjustments in the cheese production process at TINE Jæren. A spin-off innovation project called Smart Cheese Process has been funded by FFL/JA, where TINE and the automation company Au2mate will implement data- and model-driven solutions for real-time process control, in collaboration with Nofima and SINTEF Digital.

Two master projects have been completed within the MODEL project in 2024. In the first project, student Melvin Uthayaseelan compared different machine learning algorithms for predicting dry matter in cheese based on the TINE data. He compared both the predictive ability and the identification of important. In the second project, students Pradeep Manoraj and Trishaban Jegatheeswaran compared different algorithms for semi-supervised regression. These are methods that can be used in situations where we have response measurements for only a small subset of the data set, as is the case for the data collected at Bioco.

CONSUMER

Quality measurements open new possibilities for marketing and product development. To realize this potential, we need to understand how consumers will react to quality differentiation, how best to communicate/market such products, and how this may affect the value and consumption of different product categories. How could the food companies in DigiFoods utilize existing or future data on product quality for product development, shelf-life extension and/or marketing?

Case study with Tine
(part of Åse Grendstad's PhD)

Background: When it comes to yoghurt, better understanding of yoghurt quality parameters that influence shelf life in relation to consumer acceptance/rejection is key to design product and quality assurance strategies, communication, as well as reducing food waste.

Studies show that the date label have a significant effect on food waste. While labels, often accompanied by phrases like "Best before, often good after," encourage consumers to use their senses to assess food quality, many consumers still rely exclusively on the date labels. Altered taste, consistency, and whey separation during storage are known to negatively impact sensory quality of fermented products.

Materials and Methods: A mixed methods approach was utilised, where a quantitative consumer study was run online, to better understand yoghurt quality requirements from a consumer perspective. Two focus groups, each with 8 participants, were conducted to support the survey design, focusing on yoghurt purchasing habits, quality defects, and food waste behaviour, etc. The survey (n=298) explored consumer perceptions of yoghurt,

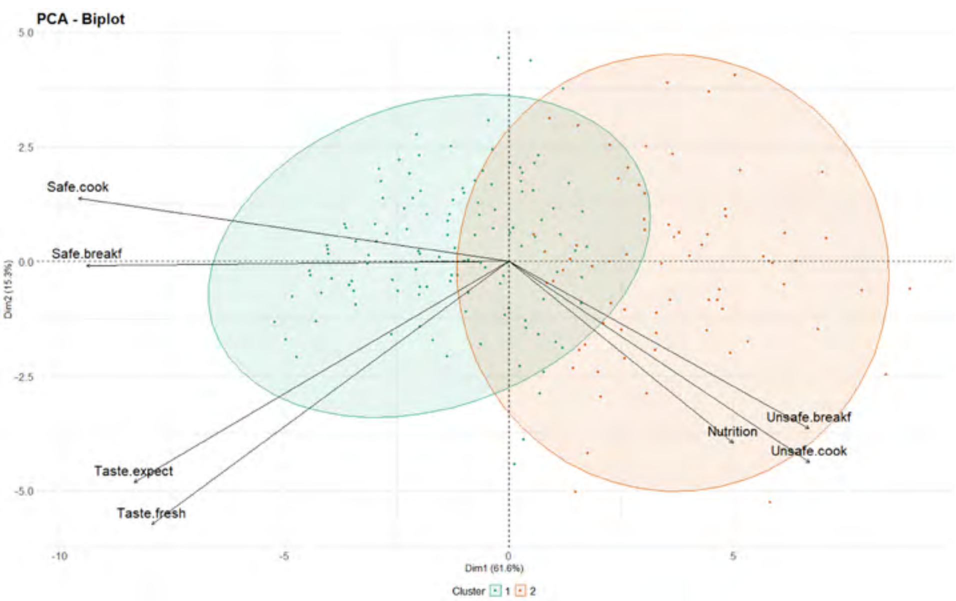
Two yoghurt samples evaluated in a conjoint test during the consumer survey.
The samples illustrate the different factor levels: date-label (two weeks before / two weeks after), yoghurt appearance (with/without surface whey), and package. instruction (with / without instruction text).

focusing on aspects such as shelf-life, package information and whey separation. Participants assessed their willingness to consume, based on photos and videos of eight yoghurt samples, in a conjoint test. The survey also contained attitude- and demographic measures. The consumers where segmented based on demographics and attitudes. This research builds upon previous findings by examining the role of labelling and sensory quality in affecting consumers decisions, offering deeper insights into factors influencing yoghurt consumption.

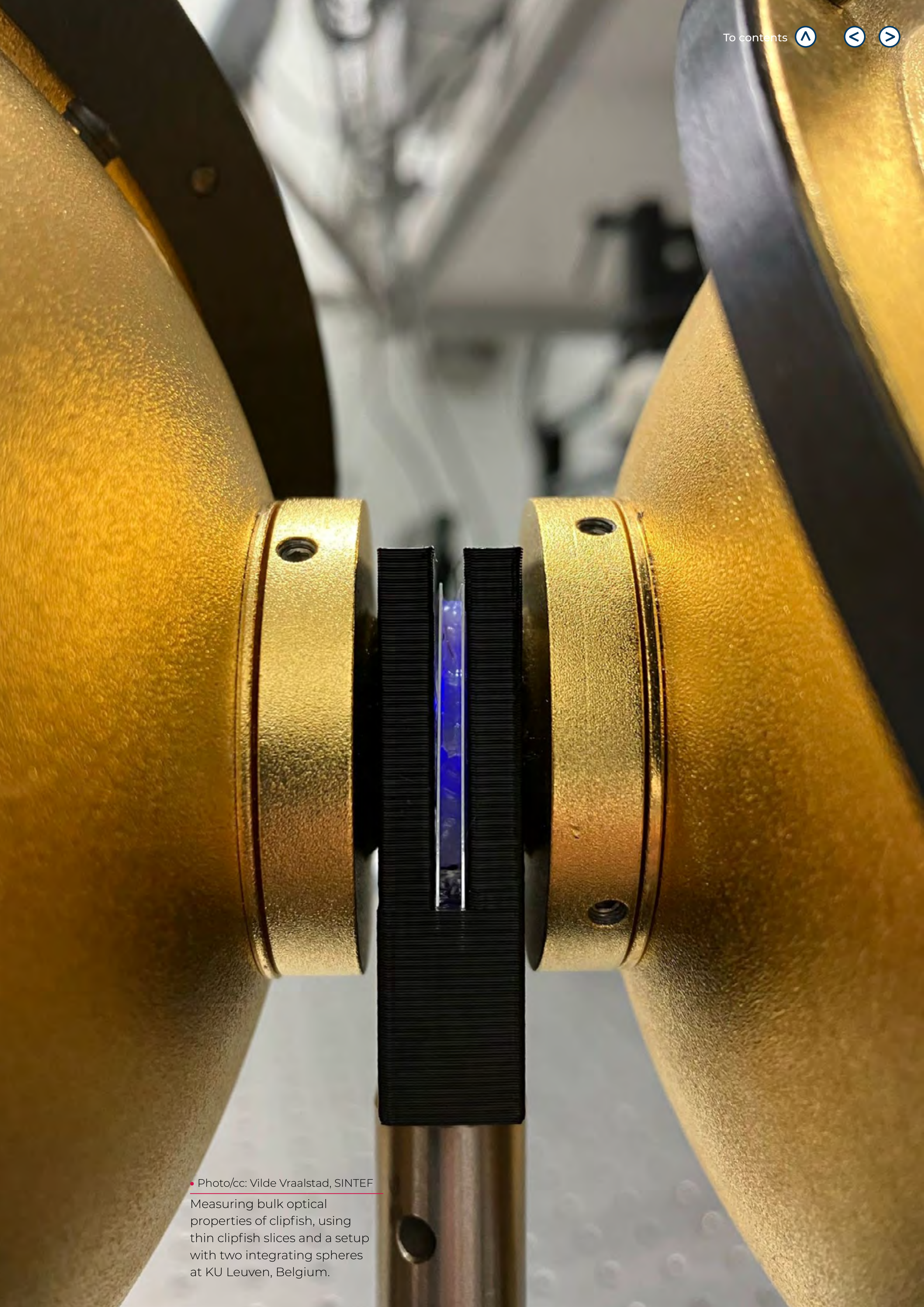
Results: Date label and yoghurt appearance significantly influenced consumers' willingness to consume, while package information had no significant effects. Hierarchical clustering identified two consumer clusters, with Cluster 2 exhibiting greater concerns regarding safety and quality (Figure below). There was a significant interaction between consumer cluster and date label (p<0.001). Cluster 2 was less willing to consume yoghurt after the best-before date. Additional research is required to investigate further how different package information (text or visual elements) affect consumers behaviour in real-life.

Studies show that the date label have a significant effect on food waste

Dissemination: Poster presentation in Eurosense, the European Conference on Sensory & Consumer Research, September 2024 (Dublin). One manuscript in preparation has been submitted to FQAP.



Hierarchical Clustering Analysis on results of the consumer survey.



• Photo/cc: Vilde Vraalstad, SINTEF

Measuring bulk optical properties of clipfish, using thin clipfish slices and a setup with two integrating spheres at KU Leuven, Belgium.

5. International collaboration

DigiFoods has established close collaboration with three excellent foreign research groups and three foreign high-tech technology providers who are important for carrying out the research and innovation work. The research groups take active part in the running projects and share supervision of PhD-students. It is an excellent base for exchange of PhDs and post-docs.

1. **University of Lincoln (ULin),** (UK), is represented in DigiFoods by Dr. Gregorz Cielniak and his research group at Lincoln Institute of Agri-food Technology. They are contributing with expertise in autonomous and long-term navigation of agricultural robots, sensor and implement integration and data gathering, management and analysis. The university has a research farm with more than ten of Saga Robotics' Thorvald robots that can be used for extensive testing in a realistic environment. They are taking active part in MOBILESENSE.

2. **Ulm University (UUlm),** (Germany), is represented by Professor Boris Mizaikoff, director of the Institute of Analytical and Bioanalytical Chemistry (IABC). UUlm has developed miniaturized mid-infrared sensing platforms based on thin-film semiconductor, oxide/nitride, and diamond waveguides that have already demonstrated their potential for analyzing e.g., secondary structure changes in proteins. UUlm participates in the project IR and develops this platform further for in-line measurement of protein, lipid composition in foods and dairy and bioprocess control.

3. **The Polytechnic University of Valencia (UPV),** (Spain), is represented by Professor Alberto Ferrer, group leader of the Multivariate Statistical Engineering Group. The group is devoted to research, development and innovation activities in the area of multivariate statistical techniques for quality and productivity improvement and mega-database analysis. Professor Ferrer participates in the MODEL project and provides joint supervision of PhD students and on data analysis and real-time process control.

Foreign technology companies are also partners since they offer technology of interest to the centre and Norwegian food industry:

4. **MarqMetrix,** (USA), provides modern, easy to use Raman instruments for rapid material analysis and process measurements. They are represented by Dr. Brian Marquardt, world leading in development of process Raman systems and very interested in novel food applications. He is contributing with knowledge and instrumentation in project RAMAN.

5. **nanoplus Gmbh,** (Germany), is represented by Dr. Johannes Koeth. They contribute by bringing in capabilities and related expertise in the field of Quantum cascade laser (QCL) and Interband cascade laser (ICL) technology. Nanoplus' main task is to support in combining QCLs with waveguide technology developed by UUlm for online measurement of complex structures and composition in food samples online, such as fatty acid composition. This is being explored in the IR project.

6. **OptoPrecision GmbH,** (Germany), represented by Dr. Markus Naegele, is a leading company in research, development, and production of high-quality optical sensing devices and contributes by developing laser-driver and detection electronics in conjunction with the corresponding embedded software to realize a dedicated analyzer platform in Pillar 1 and project IR.

6. Recruitment, education and training

DigiFoods is planning to have a total of seven PhD fellowships and seven postdoctoral fellowships associated with our research over the lifetime of the centre. These candidates cover a large range of applications and instrumentations in the food industry. Their projects cover key areas from methodological and instrumental developments, optimal deployment and usage of sensors and analysis of process data collected with sensors.

	Location	Candidate	Funding	Project	2020	2021	2022	2023	2024	2025	2026	2027	2028
PhD-students	Nofima	Tiril Aurora Lintvedt	Nofima	RAMAN									
	Nofima	Christian Thorjussen	Nofima	MODEL									
	Nofima/UPV	Marco Cattaldo	Nofima	MODEL									
	Nofima/ SINTEF	Bijay Kafle	RCN	FTIR									
	NMBU	Andreas U.N. Persch	RCN	IR									
	TINE (Nofima)	Åse Riseng Grendstad	TINE	CONSUMER									
	SINTEF/ Nofima	Vilde Vraalstad	RCN	NIR									
	NMBU	Mehmet Can Erdem	NMBU	IR									
Post-docs	Nofima	Samuel Ortega Sarmiento	Nofima	HYPERSPEC									
	Nofima	Rowan Romeyn	Nofima	HYPERSPEC									
	NMBU	Nageshvar Patel	RCN	IR									
	NMBU	Gabriel Lins Tenório	RCN	MOBILESENSE									
	NMBU	Abhaya Pal Singh	RCN	ROBOSENSE									
	Nofima	Tiril Aurora Lintvedt	Nofima	RAMAN									
	NMBU	Maren Anna Brandsrud	RCN	IR									
	NMBU	Bijay Kafle	RCN	IR / FTIR									

The potential for further relevant master thesis topics, for students finishing in 2026 and beyond, is high

At Nofima in Ås, Tiril Aurora Lintvedt defended her PhD work on in-line Raman spectroscopy aiming for representative sampling and modelling of heterogeneous foods in May 2023. She is now hired as a postdoc within the same field of research. Christian Thorjussen is developing statistical path modelling approaches, aiming at better understanding of factors and mechanisms causing variation in food quality. Marco Cattaldo, enrolled at Universitat Politècnica de València, is developing statistical methods for process and product optimisation based on real-time measurements of food quality. Bijay Kafle defended his PhD in 2024 for building and testing an FTIR prototype system for analysis of dried liquid samples, combining development of new applications with industrial testing of the FTIR prototype. He is now working as a postdoc at NMBU on IR and FTIR technology, still with DigiFoods. Åse Riseng Grendstad started her PhD in 2022. She is funded by TINE and is working on consumer perceived quality of yoghurt as well as related spectroscopic properties. Vilde Vraalstad started her PhD work in September 2023 and she is studying opportunities and limitations in the design of well working miniature NIR sensors for food applications where measurements in depth is essential. She sits at SINTEF and collaborates closely with Nofima.

At Nofima in Tromsø, postdoc Rowan Romeyn began early in 2023. He works on strategies for combining Magnetic Resonance Imaging and other reference methods for robust industrial applications of hyper-spectral imaging, improving physical modelling and light interactions. Rowan ended his postdoc mid-2024 and is now in a scientist position at Nofima, still working in DigiFoods.

At NMBU, Mehmet Can Erdem, a member of the Biospectroscopy and Data Modeling (BioSpec) group, began his PhD in April 2023. He is focusing on the design and implementation of infrared optical devices and instrumentation. Dr. Bijay Kafle started a researcher position in DigiFoods at BioSpec in 2025, working on the applications of infrared devices for protein and fat profile measurements. Although the budget initially included a 2-year postdoc position, new regulations requiring a minimum of 3 years for postdoc positions led to his employment as a researcher instead. Dr. Maren Anna Brandsrud, co-funded by several projects, is working on waveguide sample interaction in the infrared spectrum for liquid sample measurements.

NMBU robotics attempted to hire a PhD in 2022 and 2023 to work on control of sensors to be used in complex measurements situations. It has been very difficult to recruit PhDs within robotics, but we have succeeded in hiring two postdocs in 2024. Gabriel Lins Tenório is focussing on how to operate sensors on mobile robots in the field. Abhaya Pal Singh develops robotic control of sensors at conveyor belts.

A connection to the master programs in data science at NMBU has been established by offering relevant master thesis topics for students finishing their master education in 2023. DigiFoods has recruited two master students so far in 2023 and three more in 2024. Additionally, in 2023 we recruited a student from Physics and Mathematics at NTNU for master work on sensor systems at SINTEF and she is now a PhD-student. The potential for further relevant master thesis topics, for students finishing in 2026 and beyond, is high

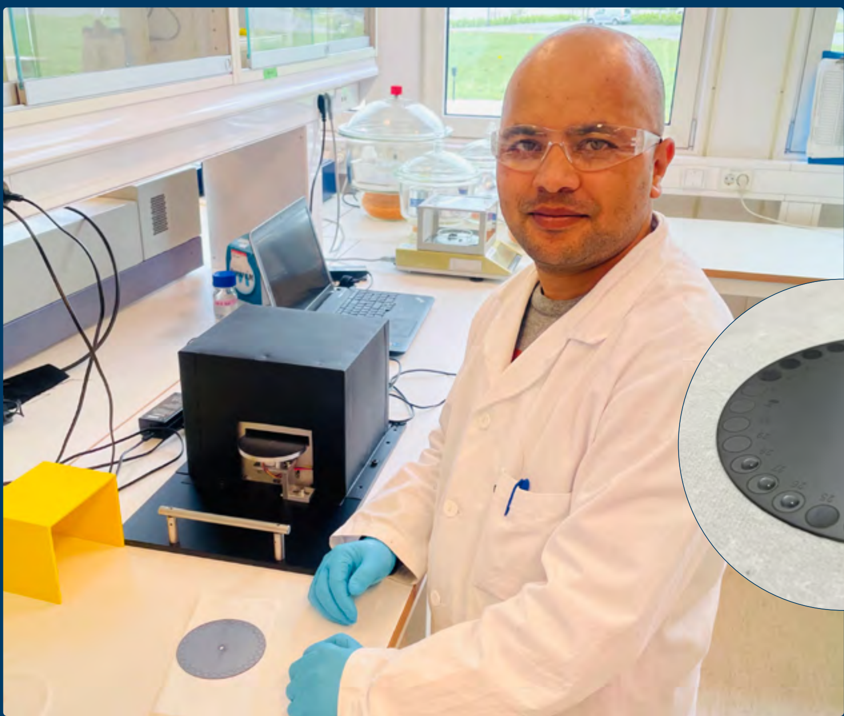
Article

Can food be medicine? This instrument finds the answer faster

by Wenche Aale Hægermark, Nofima

Can turkey carcasses or fish bones be used for medicine? Is milk suitable for making cheese? Protein measurements can provide answers, and Bijay Kafle measures food proteins in a new and better way.

Photos/cc: Ulrike Bocker, Nofima & Kathinka Dankel, Nofima *(little photo)*



Bijay Kafle with the FTIR prototype ("BumbleBee") for dry film measurements. Dried samples on the circular plate.

He has his doctorate from Nofima and DigiFoods, focusing on analyses to measure the quality of foods. "My focus is on proteins in food. With conventional methods for measuring what food contains, it takes a lot of time to measure fat, proteins, and sugars," he explains.

Proteins

Instead, he works with a technique called FTIR spectroscopy. It stands for "Fourier Transform Infrared Spectroscopy." "It's a very fast technique. It only takes a few seconds to analyze a sample," says Kafle.

Infrared spectroscopy means that the substance to be analyzed is irradiated with infrared rays. Some of the rays pass through, while some remain in the sample—they are absorbed.

The substances that food contains, such as proteins, fats, and carbohydrates, absorb wavelengths that are entirely different from substance to substance. Which wavelengths are absorbed tells which chemical substances are present in the sample.

Fingerprint

"FTIR analysis provides a chemical fingerprint of a sample. Fat has its fingerprint, sugar has its, and so do proteins," he says.

The measurements say much more than how much protein, fat, and sugar a sample contains. It can also provide information about the composition of the proteins and what kind of fat and sugar it is.

Getting rid of the water

What Bijay Kafle has worked on are proteins that are relevant to the industry. He has managed to measure them even more easily and quickly. "My doctoral thesis is about using FTIR based on so-called dry film analysis," he says.

This means that he makes a thin, dry film of a sample before the analysis. He places the film on a silicon plate that the infrared rays can penetrate.

When protein samples are dissolved in water, it is a problem that the water interferes with the measurements. The water absorbs infrared light in the same wavelength ranges as the substances to be measured. Thus, the results are not accurate. "That's why we want to dry the samples," he says.

"In other FTIR analyses, we often measure the liquid and subtract the signals that come from the water. When we analyze dry films, the water is physically removed," says Kafle. This means that the interference from water is minimal, and the measurements of the proteins are more accurate.

Bumblebee Box

He has not only worked with theory. Together with colleagues at SINTEF, he has also worked on designing and developing a portable FTIR system based on dry film analyses.

The result is a yellow and black box that is small enough to be carried to where it will be used. Colleagues call it "Bumble Bee." "Yes, someone thought it looked like a bumblebee. It can fly from industry to industry for sample measurements," smiles Bijay Kafle.

He has tested the bumblebee instrument on samples from fish, chicken, and turkey. It is about the carcasses that are left after the parts that can be used for food or feed have been utilized. "The industry uses these residual raw materials to obtain valuable substances: Peptides, free amino acids, and fats. They are used for animal feed and a little for food. We measure the quality so that the quality of the products is stable, and it is possible to find new markets in the future," he says.

Better Measurements

Dry film analysis provides more reliable results than other FTIR methods, both when the samples come from poultry and salmon. For example, FTIR can be used to show how there is more collagen—a protein so important to the body that it is sold as a dietary supplement—in the residual material from turkey than in similar residues from chicken.

In milk, the measurements not only show what kind of proteins are present and how they are composed, but also how healthy the cow is.

"This means that dry film FTIR can be used in the dairy industry, but also on the farm, now that there is a portable instrument available," Kafle states.

After having completed his dissertation last year, Bijay Kafle is now continuing as a postdoc in DigiFoods at NMBU. Here he will also continue to work with the FTIR instrument

Ready for Industry

The plan is to use the FTIR instrument in the industry, for example, to find out which protein products can become important dietary supplements or even medicines. The instrument has been thoroughly tested, and it turns out that it is as good as today's large, laboratory-based, expensive instruments.

"We now have an FTIR instrument that has been industrially tested and works, and we are working on several alternative paths for further use. The fact that the box is portable means that we can now test new applications directly with the industry, on process lines. This has not been possible before," says senior scientist Nils Kristian Afseth, who has been Bijay's supervisor.

Several major players such as Tine, Bioco, and Biomega are now participating in the further development of the FTIR instrument through the DigiFoods project. Together, they are working to make the industry's processes even more precise and efficient

Next Step

For now, the FTIR instrument requires manual handling of the sample to be analyzed. To adapt the system to automatic measurements in the process, one can imagine that the instrument is part of an automatic system where a robot arm takes samples directly from the process and handles them automatically.

"NMBU, Nofima, and SINTEF Digital have applied for funding for a commercialization project to develop an automatic measurement system. The goal is to develop a unique FTIR system that can measure directly in the production process," says Nils Kristian Afseth.

An important part of all sensor development is to develop data solutions that transfer sensor signals to chemical (or other types of) information. Such applications are often specific to each sensor system, and the development of these applications is time-consuming and costly.

"We are now developing methods to transfer existing laboratory applications directly to the FTIR instrument. This will make the transition from the laboratory to the industry both faster and more cost-effective," concludes Nils Kristian Afseth.

Article

Building a business case for novel technology

by Marion O Farrell

SenseInside is an innovation project that was spun-out from the SFI DigiFoods to verify the commercialisation potential of the early miniaturized NIR prototype developed in DigiFoods.

The miniature NIR instrument has been tested on crab meat content, strawberry and tomato sweetness, dry matter in clipfish, and fat content in salami sausages.

To conduct commercialization studies, Jens Petter Wold from Nofima and Jon Tschudi from SINTEF made an eventful journey to Lerøy in Kjøllefjord in September 2024, which is about as far north as you get in Norway. After two attempts with troublesome weather and technical issues with the plane, the determined DigiFoods team finally made it to Kjøllefjord.

In 2023, our initial attempt to visit Kjøllefjord was aborted when the flight was sent back to Tromsø just before arriving in Hammerfest, due to technical problem. This time, in 2024, Jens Petter was unlucky enough to have his flight to Mehamn aborted due to strong sidewinds before it was redirected to Tromsø. The next flight out of Tromsø was also unsuccessful and resulted in a diversion to Kirkenes, overnighting in a hotel before flying to Lakselv and driving 4 hours to Kjøllefjord, almost 24 hours later than scheduled. Jon, who had luckily arrived a day earlier, waited patiently (a tourist for the day ;-)) for Jens Petter to arrive with the SenseInside instrument so that the commercial trials could be conducted. The bigger SmartSensor prototype, against which SenseInside was to be compared, had luckily arrived by Hurtigruta a few days early just before that route was also cancelled due to the weather!

So why didn't Jens Petter and Jon give up and return home? How important is it for us to involve industry in our research? And how was the trip in the end?

Raimo Sørensen and his team at Lerøy did an excellent job preparing for our visit, and we managed to set up all the instrumentation, and complete all the scheduled experiments.

Comparing two instrument prototypes

Lerøy had ensured that we had a sample set of 20 live king crabs, which they had manually checked to ensure varying meat content, and they had prepared a place for us to do our work. But even more importantly, they got involved in the testing – they assisted us in handling, labelling, and measuring the crabs, and even got trained up so that they could control one of the prototype instruments.

All the crab legs were measured with two instrument prototypes, SmartSensor and SenseInside. This interactive research is invaluable for us in DigiFoods, making all the difference when building a business case around the newly developed measurement technology.

> Designing technology that is useful in industry places different demands on us researchers than just showing that something can be measured

One thing is measuring the crabs and knowing that the instrument works – that is something we can do ourselves in the lab with the right samples – but it is an entirely different experience to see how end-users in industry handle the crabs, how they managed to guide the legs to the instrument, how they would use a mounted instrument versus a handheld instrument, and what type of software interface is intuitive for them. And of course, the availability of live crabs is, of course, much greater in Finnmark than in the lab at Ås.

Photo/cc: Jon Tschudi, SINTEF

(Photo to the left) Meat content in cooked crab leg to match with the NIR measurement. *(Photo above)* Measurement of meat content in live king crabs with NIR spectroscopy.

King crabs with varying meat content give good sample distribution for the tests

The return journey to Oslo was also eventful, with the flight from Mehamn being cancelled, but it did mean that Jens Petter and Jon got to spend a nice evening in Kjøllefjord, followed by a scenic drive to Lakselv the next day! After the commercial trial, Lerøy slaughtered and cooked all the crabs, froze them and shipped them to Nofima for follow-up reference measurements in the lab. This allowed us to determine the performance of the instruments.

At Nofima, all the legs were cut at the correct position and inspected for meat content. This manual observation was then compared with the measurements made by the instruments at Kjøllefjord.

Lerøy had done a good job in providing us crabs with varying meat content, so we had good sample distribution for the tests. We could verify that the new smaller SenseInside actually performed slightly better than the bigger SmartSensor. And that performance was in line with earlier promising studies.

New technology need to address industrial demands

Designing technology that is useful in industry places different demands on us researchers than just showing that something can be measured. This journey from demonstration to product involves understanding how an instrument measures, its user friendliness, its size and shape, and the industry's willingness to pay.

These are all essential inputs to get technology across the ever-looming valley of death. We are now working on securing more funding so that we can get more industrial involvement. This funding would allow us to take a Minimum Viable Product (MVP) approach, which will build on what we have done in our commercial trials at Kjøllefjord in 2024 and Brødrene Sperre with clipfish in 2023.

By building a product that is not expensively over-engineered in an echo chamber, we aim to send out an early product, or MVP, with just enough features to be usable by early-adopter customers who can then provide feedback on how the final product should look, feel and function.

We are also looking for new applications and markets to test this on, as this increases attractiveness from a business perspective. We need to show that this product development track is worth investing in and get a better idea of how many we can realistically sell in the future. We also have an ongoing patent process to protect the uniqueness of the technology, which is also essential for commercialization.

We have high hopes for SenseInside – there is still work to do, but we believe in its potential!

7. Communication and dissemination

The primary objective of DigiFoods is to develop smart sensor solutions for food quality assessment directly in the processing lines, throughout the food value chains. The obtained food quality information will be used for optimization of both processes and value chains and make the food industry more efficient and sustainable.

The purpose of the communication is to present inventions and know-how from DigiFoods research as well as network development and knowledge exchange.

Our priority target groups are:

- Industry: Food and bioindustry, technology companies
- Scientific community: scientist and students
- The Public, including funding bodies and policymakers

Dissemination within the project

One newsletter (in June) has been produced and distributed via e-mails to the partners and funders.

The annual meeting took place at Hoff Industrier in Gjøvik. There were organized tours through the different facilities at Hoff. In addition, results were disseminated and needs and challenges discussed. 52 people from the different partners participated.

Photo/cc: Stine Thøring Juul-Dam, Nofima

Participants at the DigiFoods Annual meeting ready for their tour of HOFF facilities in Gjøvik.

External communication and dissemination

DigiFoods has its own LinkedIn account, where we share our latest advancements, news and upcoming events. We receive positive and valuable feedback on the posts we publish here.

During 2024 the media outreach in DigiFoods has resulted in 46 news articles in the press. 31 of these where in the Norwegian press, both trade magazines like *Teknikk Ukeblad, Kjøttbransjen, MatvareWatch* and *Fiskeribladet*, and more public media such as *Nationen* and *Forskning.no*. All international articles were in English.

Scientists and students also held more than 20 presentations in Europe and the USA, sharing insight and results from the centre, as well as hosting events for relevant scientific communities and the industry.

Together with the projects PHOTONFOOD and FoodSafeR, DigiFoods SFI took part in arranging the joint symposium "Advancements in Monitoring Food Contamination and Quality", hosted by The University of Natural Resources and Life Sciences (BOKU), Vienna at IFA-Tulln.

At the symposium, we presented research from DigiFoods, highlighting how spectroscopic techniques can be used to efficiently measure food quality and optimize food production processes.

In April, DigiFoods co-hosted the EPIC Technology Meeting on Photonics for the AgriFood Industry at Ås, Norway. The event brought together experts, researchers, and industry professionals from around the world to explore the transformative potential of photonics in agriculture and food production.

Photonics, the science of light, offers innovative solutions from farm to fork. In precision agriculture, these technologies enable farmers to monitor crop health, detect diseases early, and optimize resource use, leading to higher yields and reduced waste. In food processing, photonics ensures quality control and safety by detecting contaminants and assessing the composition of food products without physical contact.

The invited speakers, including DigiFood's own Jens Petter Wold from Nofima, Marion O'Farrell from SINTEF, Boris Zimmermann from NMBU and CEO Trond Løke from NEO, shared insights into the latest advancements in smart spectroscopic sensors and spectral imaging. These technologies enhance efficiency and sustainability in food production, paving the way for a future where food quality and safety are guaranteed through non-destructive, real-time analysis. They also address global food challenges, making our food systems more resilient, sustainable, and secure.

Besides fostering international collaboration and knowledge exchange, the meeting offered an on-site tour of both Nofima and NMBU, showcasing some of our advancements and research in the field, including sweetness measurements in strawberries and tomatoes by non-contact NIR spectroscopy and rapid determination of fatty acids in salmon fillets by Raman spectroscopy. For more information, please visit the EPIC Technology Meeting webpage.

Photos/cc: Heidi Schwartz-Zimmermann

Tullin presentations.

(Photo above) Raman lab is ready for guided tour. *(Photo below)* EPIC.

46 news articles in the press

31 of these in the Norwegian press

20+ presentations held in Europe and the USA

Article

Sensors can "see" if tomatoes are sweet enough

by Wenche Aale Hægermark, Nofima

Consumers expect that deep red cherry tomatoes have a sweet and fresh taste, but this is not always the case. This leads to dissatisfied customers, who may choose another type of tomato next time.

Photo/cc: Vilde Vraalstad, SINTEF

Frode Ringsevjen from Wiig Gartneri, wearing eye tracking glasses while picking tomatoes to help Marianne Bakken (SINTEF) investigate how human demonstration can help train artificial intelligence.

This is a situation Wiig Gartneri wants to avoid. They produce Piccolo tomatoes, red cherry tomatoes that are extra sweet, and they know that the red colour is not a guarantee of sweetness. Now they want to use sensor technology to ensure that all the tomatoes they deliver to the stores taste just as sweet and fresh as the customers expect.

Random samples can give incorrect answers

The sweetness in tomatoes comes from the fruit sugar. Today, sweetness is measured through so-called Brix measurements. This is done by squeezing juice from the tomato and measuring the sugar concentration with an optical measuring instrument called a refractometer. This method destroys the tomatoes and can therefore only be used for spot checks.

"We have discovered that sometimes the reference method Brix works poorly, without fully understanding why. At the same time, we see that NIR measurements consistently work well. It was the analyses carried out by Nofima's sensory assessors that made us discover that the Brix method can give deviating answers," says Jens Petter Wold. He leads DigiFoods and is a senior scientist at Nofima.

He adds that these results have attracted international attention and interest.

Taste tests confirm findings

In the work to develop calibrations that ensure that the NIR sensors measure the correct sugar con-

Facts about Piccolo Tomatoes
A Piccolo tomato plant in a greenhouse lives for up to 12 months, and it takes 12–15 weeks from seed to the first red tomato.
After three to six weeks, the sprout is moved to the greenhouse, and it takes about nine weeks before the first tomatoes are ready for harvest.

Photos/cc: Anders Hansen, SINTEF

Tasting cherry tomatoes.

tent, the scientists have compared results from NIR sensors, Brix measurements, and Nofima's sensory assessors panel.

The assessors panel consists of ten professional assessors, and they have analysed tomatoes that have undergone NIR measurements, and it turns out that the results are very consistent.

The ten professional assessors at Nofima are a human instrument, and their measurements are far more nuanced than mechanical instruments. Their profession is to map and assess degrees of characteristics, preferably in food and drink.

Their analyses of Piccolo cherry tomatoes show that there are several flavours that follow the sweet tomatoes, like umami and acidic taste. In this context, acid gives freshness. The sweet tomatoes also had a more fruity smell. Conversely are the tomatoes with sour and green taste.

"It has been extremely useful to have the sensory panel involved in this research. Their results ensure that we can be confident that the sugar content we measure with NIR corresponds very well with sensory sweetness," Jens Petter Wold points out.

The sugar in the tomato is evenly distributed

Another aspect the scientists have investigated is how the sweetness, i.e., the fruit sugar, is distributed in the tomatoes.

"We discovered that the sugar is evenly distributed in the tomatoes, and this is also of importance for how flexible Wiig can be in the choice of measuring instrument. When we know that the fruit sugar is fairly evenly distributed, we can also assume that it will work with measuring methods that do not measure as deeply into the tomatoes." says Jens Petter Wold.

Testing sensors available on the market

The new NIR sensor developed by SINTEF and Nofima can measure well into a range of fruits and vegetables, and this provides good and stable measurements of sugar in tomatoes. But as of today, there is no commercial instrument available.

DigiFoods partner NEO is now developing and testing a solution based on their commercially available hyperspectral (HySpex) cameras to bridge this gap.

"NEO has successfully tested this solution on tomatoes, creating a dedicated setup for in-line quality grading that delivers promising results. The system was tested in reflectance mode with polarizers to enhance the measurement quality. Given the semi-transparent nature of tomatoes, this setup appears to penetrate deeply enough to obtain reliable measurements," says Lars Gidskehaug, Solution Manager at NEO.

One advantage of hyperspectral imaging is that we can image the sugar content in each individual tomato, and this can be used to optimize quality selection and packaging of the tomatoes.

Measurements are made on the conveyor belt

When the tomato clusters are picked from the tomato plants in the greenhouse, they are placed on a conveyor belt. Today, the employees assess whether the tomatoes are good enough based on colour and remove the tomatoes they do not approve. These go to animal feed.

At the same time, we know that two tomatoes that look exactly the same can taste completely different. That is why Wiig wants a sensor to measure the sugar content in all the tomatoes. If some tomatoes do not have the sweet taste that customers want, these tomatoes are manually removed before the rest are moved to a cardboard cup.

Publication and dissemination

Peer-reviewed publications

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Vraalstad, V., Tschudi, J., O'Farrell, M., Hansen, A., Wold, JP. (2024). How a fundamental understanding of spectroscopic sensors makes robust solutions for real-world applications. Food Analytics Conference 2024, Copenhagen, Denmark, 13.11.2024.

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Wold, J.P., Lorentzen, G.E., O'Farrell, M., Tschudi, J. (2024). Rapid and non-destructive quantification of meat content in the legs of live red king crab (Camtschaticus paralithodes) by nearinfrared spectroscopy. SensorFINT Final Conference, Córdoba, Spain, 29–31.05.2024.

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Jegatheeswaran, T. (2024). Prediksjon av kvalitet og mengde proteinhydrolysater fra kylling-restråstoff. Master thesis, NMBU.

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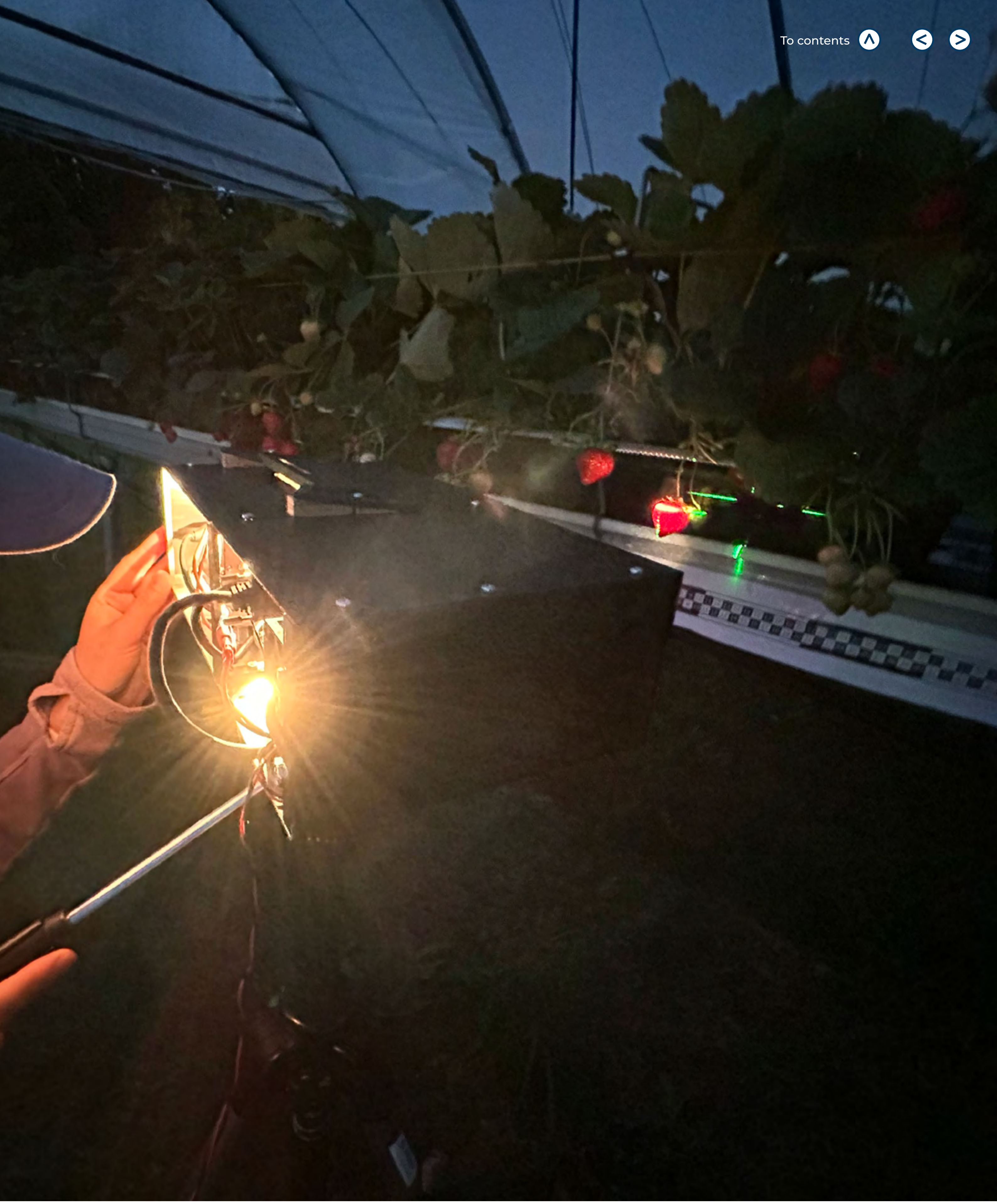


• Photo/cc: Anders Hansen, SINTEF

Field studies to investigate the performance under varying light conditions of our strawberry sweetness sensor FragoPro.

8. Administration

Key personnel

Postdoctoral researchers with financial support from the Centre budget

Name	Period	Topic
Rowan Romeyn *	2023–2026	Hyperspectral imaging for food analysis
Gabriel Lins Tenorio	2024–2027	Synchronized Navigation and Manipulation
Abhaya Pal Singh	2024–2026	Integration of sensors with robotics
Tiril Aurora Lintvedt	2023–2026	Applied Raman spectroscopy
Maren Anna Brandsrud	2025–2026	IR Instrumentation
Bijay Kafle	2025–2026	IR and FTIR technology

* Romeyn was hired as a Researcher in Nofima in August 2024

PhD students with financial support from the Centre budget

Name	Period	Topic
Bijay Kafle	2021–2024	Dry-film FTIR spectroscopy for in-process food quality measurements.
Mehmet Can Erdem	2023–2027	IR instrumentation
Tiril Aurora Lintvedt	2020–2023	Raman spectroscopy for in-line food quality sensing
Christian Thorjussen	2021–2024	Path modelling in agriculture and food industry
Marco Cattaldo	2021–2024	Data fusion and process optimization/control
Vilde Vraalstad	2023–2026	Fundamentals of applied NIR spectral measurement solutions

PhD students with financial support from other sources

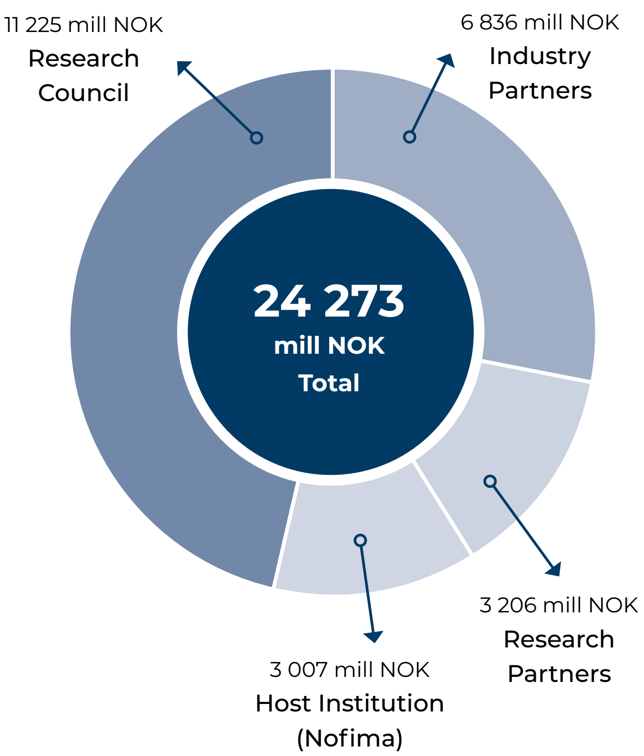
Name	Funding	Period	Topic
Åse Riseng Grendestad	TINE	2022–2026	NIR & Consumer studies

Key researchers

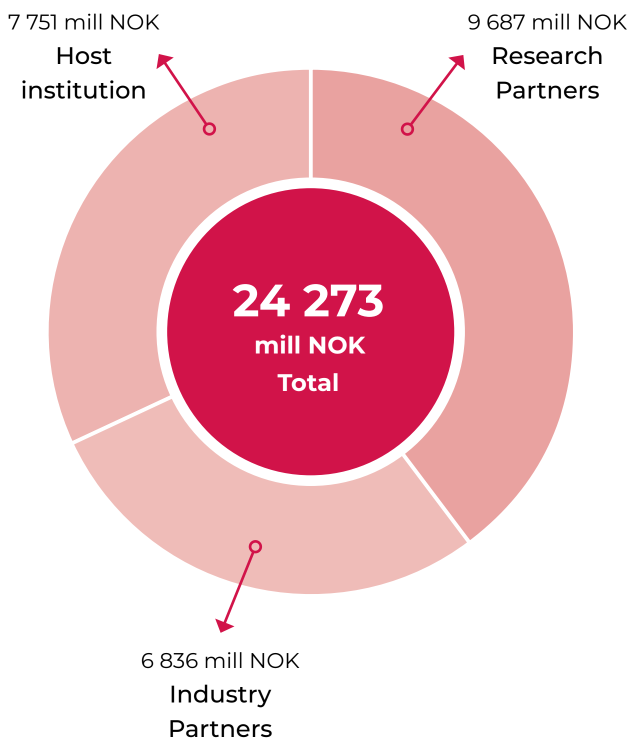
Name	Institution	Pillar	Main research area
Jens Petter Wold	Nofima	1,2,3	Applied spectroscopy and food science
Karsten Heia	Nofima	1	Applied spectroscopy
Kate Anderssen	Nofima	1	Applied spectroscopy
Petter Andersen	Nofima	1	Applied spectroscopy and food science
Rowan Romeyn	Nofima	1	Hyperspectral imaging applied to food quality analysis
Samuel Ortega	Nofima	1	Hyperspectral imaging applied to food quality analysis
Sileshi Gizachew Wubshet	Nofima	1	Analytical chemistry
Nils Kristian Afseth	Nofima	1,3	Applied spectroscopy and chemistry
Erik Tengstrand	Nofima	3	Applied spectroscopy and chemometrics
Lars Erik Solberg	Nofima	3,4	Data analysis
Ingrid Måge	Nofima	4	Multivariate data analysis
Paula Varela	Nofima	4	Sensory and consumer science
Valérie Lengard Almli	Nofima	4	Sensory and consumer science
Achim Kohler	NMBU	1	Applied spectroscopy and physics
Boris Zimmermann	NMBU	1	Applied spectroscopy and chemistry
Volha Shapaval	NMBU	1	Spectroscopy and biotechnology
Antonio Candea Leite	NMBU	2	Robotics
Nils Bjugstad	NMBU	2	Agricultural technology
Pål Johan From	NMBU	2	Robotics
Weria Khaksar	NMBU	2	Robotics
Kristian Hovde Liland	NMBU	4	Data analysis
Kari Anne Hestnes Bakke	SINTEF	1	Optical measurement systems and smart sensor systems
Tim Dunker	SINTEF	1	Optical measurement systems and smart sensor systems
Trine Kirkhus	SINTEF	1	Optical measurement systems and smart sensor systems
Anders Hansen	SINTEF	1,2	Optical measurement systems and smart sensor systems
Gregory Bouquet	SINTEF	1,2	Optical measurement systems and smart sensor systems
Jon Tschudi	SINTEF	1,2	Optical measurement systems and smart sensor systems
Marion O`Farrell	SINTEF	1,2	Optical measurement systems and smart sensor systems
Simon Pearson	Uni. Lincoln	2	Agricultural robotics
Grzegorz Cielniak	Uni. Lincoln	2	Agricultural robotics
Boris Mizaikoff	Uni. Ulm	1	IR spectroscopy
Alberto J. Ferrer-Riquelme	Uni. Valencia	4	Process modelling and control

Annual accounts

Funding



Costs



• Photo/cc: Saga Robotics

Saga Robotics' autonomous robot 'Thorvald' is starting a treatment on grapevines in Paso Robles, California. The robot irradiates the plants with UV light, controlling mildew without any chemicals. The treatment must be done at night to achieve the same effect as the traditional chemical-fungicides it replaces.

SFI Digital Food Quality (short named DigiFoods) is a centre for research-based innovation (SFI) with the purpose of developing smart sensor solutions for food quality assessment directly in the processing lines, throughout the food value chains.

digifoods.no

Norwegian Centre for Research-based Innovation