AGRIFOOD

INTRODUCTION OF THE APPLICATION FIELD[1]

Agriculture is one of the biggest industries worldwide with a market size of approximately 12 trillion dollars, accounting for 26 per cent of global employment in 2018. As a result, the demand for resources for agriculture is enormous and is not sustainable in the long term. For instance, agriculture irrigation already accounts for 70% of water use worldwide,[2] nitrogen deposition in agricultural areas resulted in a decrease in biodiversity, and overuse of fertilizer has led to phosphorus shortages. Therefore, the need for more sustainable agricultural production is urgent.

Precision agriculture is a farming management concept using digital techniques to monitor and optimise agricultural production processes, intending to increase the quantity and quality of agricultural output while using fewer resources (water, labour, fertilizers, energy, pesticides, etc.), thereby saving costs and reducing environmental impact. Precision agriculture technologies such as global positioning systems (GPS) are in widespread use and show an uptake comparable to other agricultural technologies. However, the adoption of *variable rate* technology, which allows farmers to apply fertilizer, water, chemicals, and seed at different rates across a field, rarely exceeds 20% of farms.[3] A determining factor for the adoption of precision agriculture is the balance between cost and benefit, as farmers expect a clear return on investment while budgets are limited, especially on medium and small farms. In addition, an important sucess factor is the ease-of-use and the level of integration of the sensor technology into the workflow of the farmer. So, there is a need for cost-effective, reliable and robust sensor systems.

Food processing 4.0 aims to reduce production costs, save energy, labour, and other resources, as well as diminish food loss and waste while improving the quality and safety of processed food products by using smart sensors, robotics, and data technologies. The uptake of Industry 4.0 in the food industry is estimated to be 20% to 40%, which is relatively low compared to the oil and gas industry and the automotive industry.[4] This may be related to low investment in new technologies in the food processing industry, as on average, the major food processing companies spend 1.4% of revenues on R&D.[5] In comparison the big tech companies spent 7-21% of their sales in R&D in 2020.[6]

Photonic Integrated Circuits (PICs) have great potential in the fields of agriculture and food production, as they have the potential to provide small, low-cost, and reliable sensing systems with low power consumption. The integration of PIC-based sensors in agriculture can revolutionize the way we monitor crops, optimize yields, and detect diseases. In food production, PIC-based sensors can be used to ensure efficient processing using real-time process control and to ensure food safety. The development roadmap for PICs in agriculture and food

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[2] OECD.org (last accessed 6th September 2023).

[3] Lowenberg-DeBoer and Erickson (2019), https://doi.org/10.2134/agronj2018.12.0779

[4] https://www.foodnavigator-asia.com/Article/2019/10/09/Flexibility-food-safety-and-productivity-Three-proven-benefits-of-Industry-4.0-for-the-food-and-beverage-industry-Tetra-Pak (last accessed 6th September 2023).

[5] https://www.forbes.com/sites/hankcardello/2019/03/29/why-big-food-companies-like-kraft-heinz-arent-cutting-the-mustard/?sh=7ea262bf710e (last accessed 6th September 2023).

[6] https://www.statista.com/chart/27214/companies-that-spent-the-most-on-research-and-development-in-2020/ (last accessed 6th September 2023).

production must not only consider technological challenges but also the specific requirements of the AgriFood industry. This roadmap will outline the steps required to develop and implement PICs in agriculture and food production and will highlight the potential benefits of this technology for the agriculture and food industry and for society.

The possible applications of photonic sensing vary along the agricultural supply chain, which consists of 1) Agricultural production, 2) Post-harvest handling and storage, 3) Food processing and packaging, 4) Distribution, 5) Food retail and food service, and 6) valorisation of food and agricultural waste (Figure 1).

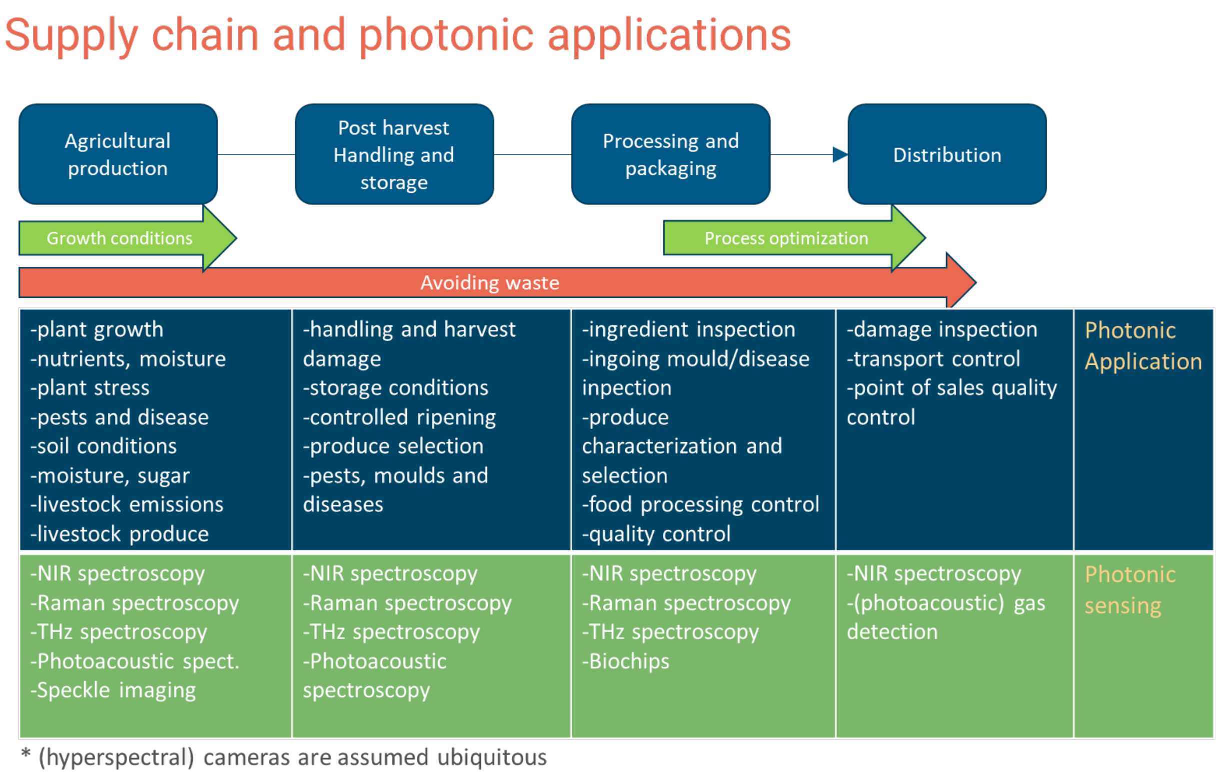

Figure 1. Application of photonics in the agrifood supply chain (figure courtesy of PhotonDelta).

APPLICATION SPECIFIC REQUIREMENTS

Extensive reviews are available on the application of photonics in agrifood applications.[7] Below we provide a short introduction to each agrifood field where it is expected that PICs will have a major impact. An overview of agrifood applications and suitable PIC modules is given in Table 1.

Agricultural production

Precision agriculture can be regarded as a toolbox of digital technologies including auto guidance using global positioning and proximity detection systems, yield monitoring and mapping, variable rate technology, grid or zone soil sampling, and electrical conductivity. Precision agriculture technologies that provide information about

[7] For example - Tan, J.Y.; Ker, P.J.; Lau, K.Y.; Hannan, M.A.; Tang, S.G.H. Applications of Photonics in Agriculture Sector: A Review. *Molecules* **2019**, *24*, 2025. https://doi.org/10.3390/molecules24102025

entire fields, orchards, or greenhouses, such as the use of GPS and weather information are widespread. As technology improves there is a trend towards proximal plant sensing and proximal soil sensing. Relevant parameters for growth control of crops are growth monitoring, water uptake, transport and transpiration monitoring, and metabolite and ionic content monitoring in leaves, stems, and fruit. This includes the measurement of sugar levels, chlorophyll, phytonutrients, and many other substances of importance for plant health. Also, measurement of pests, pesticides (including pesticide residues) and contaminants are of interest. Sensing systems for agricultural production need to take into account variable light conditions, movement of plants, e.g. due to wind, moisture, and dust.

Post-harvest processing

Post-harvest processing describes the processing of fruit and vegetables after harvest, during storage and transport. From the scientific research, several PIC-based sensor applications can be foreseen, that may revolutionize the way agricultural products are managed and preserved. In the context of preventing losses, novel sensors may play a crucial role by enabling real-time monitoring and assessment of produce quality. Also, it will be possible to detect the ripeness of fruits and vegetables, helping to prevent losses caused by unripe or overripe produce entering the wrong path in the supply chain. Additionally, they facilitate the identification of handling and harvest damage, providing insights into the optimal handling practices to minimize physical impairments, and facilitate the selection of produce based on their quality. This allows for more informed decisions in the sorting and distribution process, reducing wastage and ensuring that the products are used for the application that fits with their. Furthermore, there are opportunities for PIC-based sensors to combatting pests, moulds, and diseases by enabling the early detection of potential threats through non-invasive methods such as hyperspectral imaging, allowing for timely interventions to safeguard the produce.

In the pursuit of enhancing quality and yield, the application of photonic integrated circuits is expected to enable the optimization of storage conditions by monitoring and controlling factors like temperature, humidity, and gas concentrations within storage facilities. This ensures that agricultural products are kept in environments conducive to prolonging their freshness and minimizing spoilage. Moreover, photonic sensors may contribute to controlled ripening to ensure optimal trade-off between shelf-life and taste (e.g. ready-to-eat avocados, bananas, tropical fruits) by precisely regulating exposure to light and other environmental factors. Novel sensors will also assist in efficient produce selection by employing spectral analysis to identify attributes such as colour, size, and ripeness. This empowers farmers and distributors to make informed decisions during the sorting and grading stages, ultimately increasing market value and reducing waste. In these ways, the application of photonics is expected to contribute to post-harvest management, minimizing losses and enhancing the overall quality and yield of agricultural products. Sensing systems for agricultural production need to consider variable light conditions, large temperature differences, and vibrations during transport or sorting.

Livestock

The application of PIC-based sensors in livestock management marks a significant advancement in the agricultural industry. Sensors play a pivotal role in ensuring the well-being and productivity of livestock by monitoring various parameters. They enable real-time assessment of feed and water quality, ensuring that animals receive optimal nutrition and hydration. Moreover, sensors facilitate the tracking of livestock movement, aiding in the prevention of straying and enabling more efficient herding practices. Sensors also contribute to monitoring growth rates, detecting anomalies that might indicate health issues. By gauging stress levels, sensors provide insights into animal welfare, allowing for timely intervention. They are also instrumental in monitoring health metrics and vital signs, facilitating early disease detection and prompt treatment. Another opportunity is tracking emissions, contributing to environmental sustainability efforts in livestock farming. In sum, the application of PICs may revolutionize livestock management, promoting healthier animals, efficient resource utilization, and improved overall agricultural practices. Sensors for livestock need to be robust and shock resistant. The environment in the barn and on the pastures may dusty and humid, and light conditions may vary.

Food processing

For food processing, promising applications for PIC-based sensors are the assessment of ingredient quality, real-time process control, the measurement of product properties of the final food product, as well as the assessment of food safety along the production process.

Inspection of ingredient quality is a routine activity in the food industry. Currently, ingredient quality is assured by laboratory analyses. This includes chemical characterisation and physical characterisation (for instance particle size, viscosity, or gelling). Typically, food companies rely on specification sheets provided by ingredient suppliers, but additional characterisation often needs to be performed. However, this process takes time and as a result, additional storage capacity is required for ingredient storage.

Process control in the food industry is often based on measurement of time, temperature, pH and pressure. Additionally, for inspection and grading of fruit, vegetable and grain ingredients computer vision is now commonly used. However, information on changes in the product composition during the process is mainly obtained by laboratory analyses. Often, the lead time of these analyses is several hours to days, and as a result, real-time process control based on product composition is not possible. So, there is a huge potential for the application of photonic-based spectroscopic sensors that can provide information on product composition for real-time process control.

The main product properties are the chemical composition, flavour and texture. Currently, these properties are assessed using laboratory analyses, which is a laborious and time-consuming process.

Chemical composition

The chemical composition of food products is classified as macronutrients (proteins, lipids, carbohydrates and fibre; present at g - kg levels), micronutrients (vitamins and minerals; present at ppb - ppm levels), as well as phytochemicals (e.g. terpenoids and phenolic compounds) and flavour components (e.g. ethanol, acetic acid). Spectroscopy techniques, including NIRS, MIRS, and Raman are suitable technologies for determining the chemical composition of food products. For instance, FT-IR is routinely used to determine the macronutrient composition of milk. The suitability of these techniques depends on the concentration of the relevant components and on the complexity of the food matrix.

Texture

The texture of food products, which includes aspects such as firmness, viscosity, crispiness, gelling and mouthfeels, is another important quality parameter of food products and can be an indicator of freshness and shelf-life. As the texture is often related to water distribution, suitable spectroscopic methods are those that can image the water distribution in a product, such as NIRS and THz imaging.

Flavour

The flavour is an important factor in the quality of food. It is important for consumer acceptance, and can also be an indicator for deterioration of the product, either by physical or chemical processes (e.g. lipid oxidation) or by bacterial growth. Flavour consists mainly of odour and taste compounds. Odour compounds are volatile and suitable techniques to detect their concentration are, for instance, photoacoustic spectroscopy or laser absorption spectroscopy. However, often the concentrations of volatiles are low (ppb levels) and many different flavour components are present, which complicates the data interpretation of spectroscopic methods. For instance, more than 1,000 volatile components have been identified in coffee.[8] In food production environments, moisture, dust, vibrations, and noise are ubiquitous and temperatures may vary. Therefore, sensor systems should be designed to be resistant to these external factors.

Food safety

Food producers are legally required to ensure the food safety of their products. People have the right to expect the food they eat to be safe and suitable for consumption.[9] Also, food safety issues can affect brand's reputations. Food safety includes microbiological, physical, and chemical safety.

Microbiological food safety includes contamination of food with bacteria, yeasts, moulds, and viruses. Presence of these micro-organisms may result in food spoilage, food poisoning or infection with pathogenic bacteria. Microbiological quality of food products is routinely performed, often by plate count techniques. Microorganisms have the potential to grow in food product during shelf-life. Therefore, the EU has set strict specifications for the presence of microorganisms and especially pathogens in food. For instance, the limit for *salmonella* in milk powder and whey powder is "absent in 25 g of product placed on the market during their shelf-life".[10] Although many publications are available related to sensor development for pathogen detection in food, the low limits of detection that are required are a serious limitation for the adoption of photonic sensors for food safety control, as in most cases a time-consuming enrichment step is necessary.[11]

Physical food safety is related to the presence of foreign matter or to parts of the food itself which represent a hazard upon consumption. Examples of the former are pieces of glass, pieces of metal from processing equipment, jewellery, hairs, nails, as well as (pieces of) plants and animals. Relevant photonic sensing technologies are in the visible range (400-700 nm), infrared range (700-1000 nm), and terahertz range (30 µm – 3 mm). For the application it is important that the total product can be scanned quickly (<1/s). Often imaging is used, for instance using hyperspectral and RGB cameras. A small form factor is not required.

Chemical food safety is related to chemical components in food that may harm human health. It includes contaminants from the environment, residues of veterinary medicinal products, residues from pesticides and herbicides, as well as food contact materials and processing aids. Generally, these contaminants are present in low concentrations (ppt - ppb levels).

[8] Cordoba, et al. (2020) https://doi.org/10.1016/j.tifs.2019.12.004
[9] FAO.org (last visited 6th September 2023).
[10] Commission Regulation (EC) No 2073/2005 of 15 November 2005 on microbiological criteria for foodstuffs
[11] For example - Xue et al.(2023) https://doi.org/10.1016/j.tifs.2023.04.015

Food Waste

PIC-based sensors may be a game-changing technology for food waste prevention and valorisation. By continuously monitoring factors such as temperature, humidity, and gas concentrations, photonic sensors may ensure optimal storage conditions, extending the shelf life of perishable items and significantly reducing food spoilage. Additionally, real-time tracking of food throughout the supply chain, enabling timely interventions to redirect surplus produce to areas of need, thus preventing unnecessary waste, is an important opportunity to reduce food waste. Another opportunity is food waste valorisation by contributing to the development of innovative methods for repurposing discarded food. Through spectroscopic analysis, edible portions from food waste can be identified and sorted, supporting the creation of value-added products such as compost, biofuels, and bioplastics. Overall, the application of PICs may contribute to a holistic approach to tackling food waste, from its prevention through smarter management to its transformation into valuable resources, fostering a more sustainable and efficient food system.

Outlook

We have shown that Photonics Integrated Circuits (PICs) have great potential in the fields of agriculture and food production, as they have the potential to provide small, low-cost, and reliable sensing systems with low power consumption. Especially for agricultural applications PIC based sensors are a good fit, looking at the low investment room in the sector, and the possible integration into robotic systems and drones. For food processing, PIC based sensors open the possibility to monitor the processes using multiple low cost sensors, to optimize process control. When developing a roadmap for PICs in agriculture, it is essential to consider the diverse range of products within this industry. Agriculture encompasses a broad range of crops and livestock, each with unique characteristics and requirements, and the food production industry covers a vast array of products, from fresh produce to processed goods. Thus, the development of PICs for these industries should be customized to meet the specific needs of each product and production process. A general roadmap for PIC-based sensors in agrifood is shown in Figure 2. To a large extent, the agrifood Roadmap follows the 2023 sensors roadmap.[12] However, essential enablers of PICs in agriculture are the low cost of sensors, the wide availability of cloud computing, and the use of Artificial Intelligence (AI) to automatically generate models from PIC data. A deep understanding of the industry, collaboration with stakeholders, and a flexible approach to technology development are also crucial factors to consider. By taking into account the diversity of products and their respective requirements while leveraging these essential enablers, the development roadmap for PICs in agriculture and food production can be optimized to provide the greatest benefit to the industry and society.

[12] 2023 IPSR-I Roadmap Sensors Chapter

Table 1: Overview of agrifood applications and suitable PIC modules.

Domain: Plants & fruits

Stage	Property	PIC Modules	Main challenge
Preharvest	Plant Morphology	Lidar, 3D Imaging	Cost, mobile lidar scanner speed
	Plant Moisture	THz (100 GHz - 2 THz)	Cost reduction, waterproof, low weight, Thermally stable operation
	Sap flow	Laser Speckle (600 - 650 nm laser)	to make it cheap, robust, easy-to-use, as well as data fusion
	Plant Nutrients	NIRS (800 - 2400 nm)	Improving spectral resolution and extending the wavelength to 2400 nm.
	Fruit Ripeness	NIRS (800 - 2400 nm)	Improving spectral resolution and extending the wavelength to 2400 nm.
	Pests & diseases	Hyperspectral imaging	Algorithm development
	Moulds	Hyperspectral imaging	Algorithm development, sensitivity, e.g. to detect minute change in the reflectance spectrum due to fluorescence.
	Pesticides	Raman (SERS; 350 - 1700 nm)	Detecting ppb levels, reproducibility
Postharvest	Handling and harvesting damage	Hyperspectral imaging	Algorithm development
	Optimize storage conditions	Gas sensing, laser absorption spectroscopy, photoacoustic spectroscopy	Cost, detecting ppb levels
	Controlled ripening	Gas sensing, laser absorption spectroscopy, photoacoustic spectroscopy	Cost, detecting ppb levels
	Produce selection	Hyperspectral imaging	Algorithm development
Domain:	**Lifestock**		
	Feed & water quality	NIRS (800 - 2400 nm)	Improving spectral resolution and extending the wavelength to 2400 nm.
	Emission gases	Gas sensing, laser absorption spectroscopy, photoacoustic spectroscopy	
Domain:	**Food Processing**		
Product properties	Composition	NIRS (800 - 2400 nm), MIRS (2400 - 11000 nm), Raman (875 nm laser, 300-1800cm-1)	MIRS tunable lasers, algorithm development
	Flavour	Gas sensing, laser absorption spectroscopy, photoacoustic spectroscopy	Low concentration

Food safety	Microbiological	Fluorescence, biosensing	Biosensing: reusability
	Physical	THz imaging (0.1 – 4.0 THz)	Laser integration technology
	Chemical	NIRS (800 - 2400 nm), MIRS (2400 - 11000 nm), Raman (875 nm laser, 300-1800cm-1)	Detection sub ppb levels, MIRS tunable lasers, algorithm development

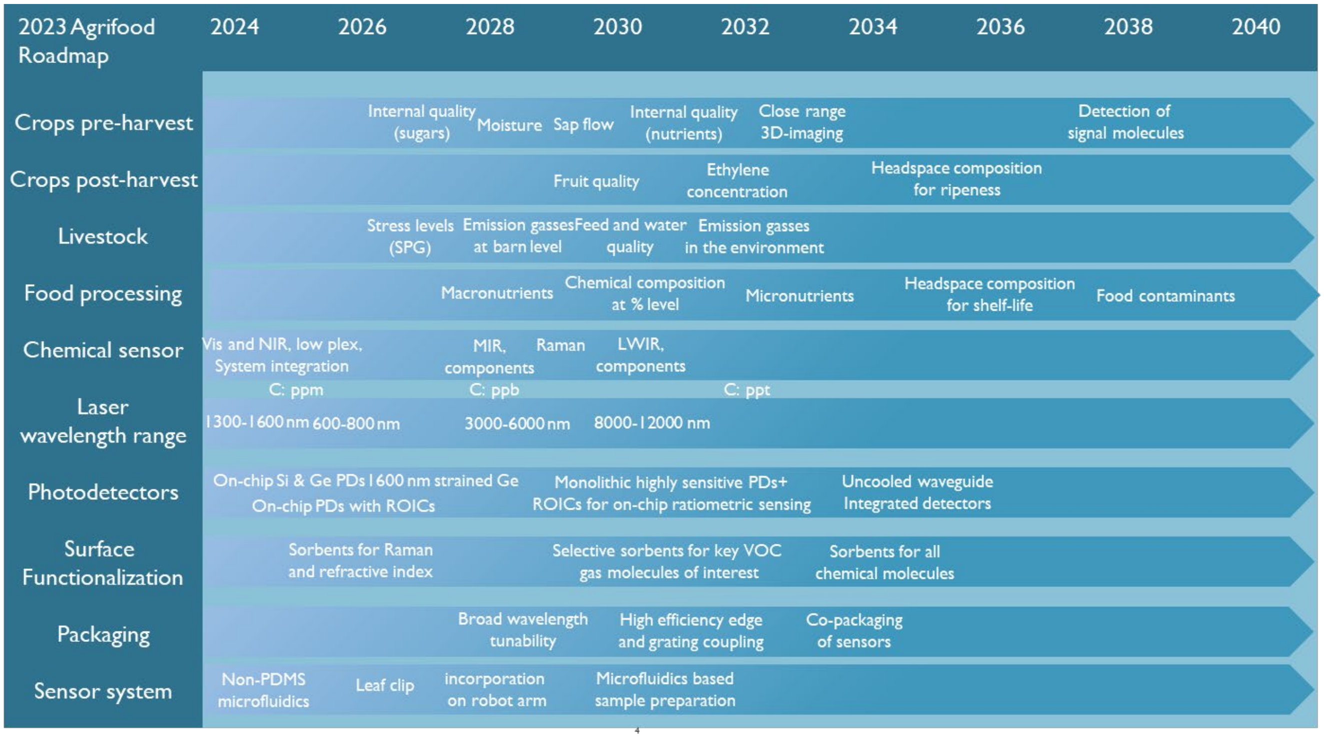

Figure 2. PIC agrifood roadmap 2024.