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ADVANCED PHOTONIC TECHNOLOGIES IN PRECISION AND DIGITAL AGRICULTURE

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Abstract: Photon-based technologies, grounded in the controlled application of light energy, are becoming a key component of modern digital and precision agriculture. This article examines three complementary approaches: laser-based targeted weed control, UV-C light for managing fungal diseases, and laser-induced breakdown spectroscopy (LIBS) for soil analysis. Each of these technologies offers high spatial and spectral selectivity, automation potential, and the ability to reduce reliance on chemical agents and conventional laboratory diagnostics. We present the scientific foundations of each approach, current applications, agronomic effects, and technical challenges, and analyze their potential integration into broader agro-digital systems. Special emphasis is placed on the role of photonics in the transition toward environmentally responsible, low-input, and data-driven food production. This contribution provides a foundation for further research and practical implementation of these technologies across diverse crop production models.

Key words: *photonics, laser-based weed control, UV-C radiation, LIBS, soil analysis, precision agriculture, agricultural digitalization, agro-optical technologies*

INTRODUCTION

Over the past two decades, agriculture has been increasingly oriented toward data-driven and technologically enhanced systems grounded in the principles of sustainability, efficiency, and precision [8]. This transformation commonly referred to as precision agriculture (PA), digital agriculture, or smart farming encompasses a wide range of technologies aimed at optimizing agronomic decision-making based on spatial, temporal, and biological data.

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One of the fastest-growing yet still underintegrated segments of this paradigm is photonics the science and technology of using light to detect, process, and interact directly with biological systems. In agricultural contexts, photonics refers to the application of optical approaches including laser, LED [7], UV, and spectroscopic technologies for monitoring plants, soil, and the environment, or for conducting precise interventions without the use of chemical agents. As an interdisciplinary field, it merges the physics of light, sensor technology, plant biology, and agronomic practice. Photonics offers high spatial and spectral selectivity, rapid responsiveness, and automation capabilities, positioning it at the forefront of developing environmentally responsible technologies for crop production. This paper explores three key areas of advanced photonic technology applications in agriculture:

- Laser-based targeted weed control, which provides a precise and environmentally friendly alternative to herbicides. Through the integration of computer vision, artificial intelligence, and high-energy laser beams, this method enables selective ablation of weeds without mechanical soil disturbance or damage to the cultivated crop.
- The use of ultraviolet-C (UV-C) radiation for fungal disease suppression in plants as a substitute for conventional fungicides. UV-C light, with wavelengths between 200 and 280 nm, damages the nucleic acids of pathogens and inhibits sporulation, leaving no chemical residues in plant tissues or the environment.
- Laser-induced breakdown spectroscopy (LIBS) as an innovative method for soil analysis. LIBS enables rapid, multi-element, reagent-free quantification of macro- and micronutrients in soils, supporting precision fertilization and sustainable fertility management.

All three technologies share common characteristics: they enable contactless, selective, and often automated operation; they do not require chemical inputs; and they are suitable for integration with existing digital platforms such as robots, unmanned aerial vehicles, and sensors. Furthermore, these technologies are increasingly paired with artificial intelligence and machine vision, allowing for complex real-time detection and response. There is a growing body of literature demonstrating the efficacy of these photonic approaches. For example, laser systems developed by companies like Carbon Robotics [3] have achieved up to 95% weed control efficacy in field trials without phytotoxic effects. Night-time UV-C treatments have reduced powdery mildew incidence in cucumbers by more than 80% without negatively impacting photosynthetic efficiency. In soil diagnostics, modern LIBS platforms have shown potential to replace classical chemical analyses with accuracy comparable to reference methods such as ICP-OES.

Despite their promise, these technologies face several challenges: high initial equipment costs, the need for precise calibration and standardization protocols, and limited practitioner familiarity with their operation in agricultural practice. It is therefore essential that equipment development be paralleled by studies on the physiological, developmental, and resistance-related impacts of light-based interventions under diverse climatic and agro-ecological conditions.

The aim of this article is to present the underlying scientific mechanisms, technological implementation, and application potential of selected photonic approaches, while critically evaluating their utility and commercial prospects across various crop production models from high-tech greenhouses to extensive field systems. The article concludes with a discussion on synergies between photonic technologies and other components of precision agriculture, and outlines directions for future research and knowledge transfer to practice.

MATERIAL AND METHODS

Laser-Based Targeted Weed Control

Mechanism of Action and Scientific Basis

Laser-based weed control is founded on the focused application of a high-energy, coherent electromagnetic beam that selectively damages the apical meristems of weeds, inducing localized thermal ablation. The thermal effect leads to protein denaturation and rupture of cell membranes, resulting in irreversible necrosis of vegetative tissue. Crucial to this process is the precise targeting of high energy density pulses to regions with elevated mitotic activity, which prevents regeneration and leads to complete cell death. The most commonly used sources are high-energy pulsed infrared diode lasers, typically operating at powers between 5 and 150 W and within the spectral region around 980 nm. With pulse durations ranging from microseconds to milliseconds, local temperature increases exceeding 2000 °C can be achieved, sufficient to vaporize cellular contents or even induce plasma phenomena. Within the WeLASER project [14], successful results were recorded, achieving up to 98% weed mortality at energy doses below 10 J/cm². Target identification is conducted via multispectral image analysis [9], supported by deep learning algorithms (e.g., convolutional neural networks, CNNs), which enable the distinction between crop plants and weeds based on morphological and spectral features. High-resolution actuators (precision up to 0.5 mm) then direct the laser beam precisely to the identified target. This approach allows for selective ablation even at early phenological stages of weed development (cotyledon–2 leaf stage).

Practical Applications

In commercial settings, laser systems are primarily employed in high-value horticultural crops, where chemical control is either restricted or prohibited. The LaserWeeder™ system [3] is based on an architecture comprising several dozen synchronized laser emitters and a real-time imaging module, enabling the simultaneous treatment of thousands of targets per hour. Empirical data from Braga Fresh farms in California [3] indicate a 70% reduction in weed removal costs and over 95% weed control efficacy.
In Europe, the WeLASER project [14] is developing a fully autonomous tracked robotic platform equipped with spectroscopy-enhanced laser modules for precise intra-row weed management. Field trials on crops such as maize, sugar beet, and triticale demonstrate the potential to replace herbicides with high selectivity and minimal soil disturbance.

Companies Developing Solutions

In addition to Carbon Robotics, several European companies are advancing laser weed control technologies. For example, Futonics Laser (Germany) is developing laser sources with high photothermal efficiency.

Extensive validations are underway within public-private partnerships involving leading research institutions such as Wageningen University & Research and INRAE. The prevailing model consists of modular systems that can be mounted on conventional tractors or integrated into standalone robotic units.

Advantages and Limitations Compared to Conventional Methods

Advantages

- Agrochemical-neutral approach: Complete elimination of herbicide use, which is particularly beneficial for organic farming systems.
- Sub-millimeter precision: Minimizes the risk of off-target damage to cultivated crops.
- High level of automation: Compatible with autonomous systems for continuous, unattended operation.
- Preservation of soil biodiversity and physical integrity: Maintains soil aggregate structure and protects the soil microbiome (edaphon).
- Limitations and Constraints
- Capital-intensive initial investment: High equipment costs and the need for advanced technical training.
- Limited throughput per hectare: Current systems are optimized for horticultural or specialty crops.
- Operational complexity: Sensitive to dust, humidity, and thermal stability of system components.
- Optical safety requirements: Implementation must comply with Class 4 laser safety standards (IEC 60825-1).

Commercial Viability and Future Outlook

Laser technologies are currently most commercially established in the United States, particularly in the segment of intensive vegetable production. Return on investment (ROI) estimates for areas exceeding 80 hectares suggest payback periods of between 1 and 3 years. In Europe, implementation remains in its early stages, with several pilot projects underway and the development of rental-based business models (e.g., Robot-as-a-Service), which could lower the adoption barrier for medium-sized and specialized farms. In conclusion, laser weed ablation represents a high-tech alternative to chemical and mechanical weed control methods, demonstrating strong potential for integration into sustainability-oriented agroecosystems that demand precision, selectivity, and environmental non-invasiveness.

Application of Ultraviolet-C (UV-C) Radiation

Mechanism of Action and Scientific Basis

Ultraviolet-C (UV-C) light, within the spectral range of 200–280 nm and with peak germicidal efficacy around 254 nm, exerts its effect through photochemical damage to nucleic acids (DNA and RNA), resulting in inhibited cell division and apoptotic death of microorganisms. UV-C photons induce the formation of cyclobutane pyrimidine dimers (CPDs) and 6-4 photoproducts [14, 7], which disrupt transcription and replication processes in pathogenic microbes.

Pathogenic fungi such as powdery mildews (*Erysiphales*) and downy mildews (*Peronosporaceae*) possess some capacity for photoreactivation via photolyase enzymes, whose activity is triggered by exposure to blue light (400–500 nm). Consequently, a key insight in the modern application of UV-C in crop protection is the strategy of irradiating plants in the absence of light at night or before sunrise to avoid activation of DNA repair mechanisms in pathogens. The optimal UV-C dose is determined by balancing the minimum lethal dose for pathogens (typically 40–120 J/m²) against the sub-cytotoxic threshold for cultivated plants. Exceeding this threshold can lead to oxidative stress, photobleaching, or necrotic lesions in leaf tissue. In practical terms, fluence (J/m²) is systematically defined based on the spectral intensity of the UV source (W/m²) and the exposure duration (s), in conjunction with a mobile lighting platform positioned above the plant canopy.

Practical Applications

The most advanced implementation of UV-C technology in agriculture is based on autonomous robotic platforms (e.g., Thorvald by Saga Robotics, TRIC Robotics), which perform nocturnal irradiation of crop rows using mounted low-pressure mercury lamps or UV-C LED panels. Field trials in vineyards [10], particularly in Chardonnay grapevines, demonstrated over 90% reduction in powdery mildew incidence with weekly treatments. Similarly, trials on Fragaria × ananassa (strawberries) showed that UV-C exposure significantly reduced the incidence of Botrytis cinerea and powdery mildew [4], while maintaining yields comparable to conventional fungicide programs. In addition to fungal pathogens, UV-C radiation also affects certain arthropods. For instance, exposure of mites and thrips to sublethal UV-C doses can lead to sterilization or inhibition of development. This combined pathogen and vector suppression effect grants UV-C technology considerable practical value.

Leading Industry Applications

Among the leading technology developers in the field of UV-based plant protection is TRIC Robotics (USA), which offers nocturnal UV-C treatment services for strawberry fields using autonomous robotic platforms specifically designed to reduce fungicide use. Saga Robotics (Norway) commercializes the modular Thorvald robotic platform, equipped with integrated UV-C light modules for systematic vineyard treatment against powdery mildew and other fungal pathogens. CleanLight [4] manufactures both stationary and mobile UV-C systems, including UV-LED panels for greenhouse use, with more than 1,000 implementations across various horticultural sectors.

Noteworthy among emerging innovators is Antobot (UK), which is developing compact autonomous robotic carriers for UV-C technology, and the French company UV Boosting, which introduces a spectral-temporal modulation approach ("priming") using low-intensity UV-B pulses to activate systemic plant immunity. Both companies represent forward-looking, non-chemical plant protection strategies based on photonic technologies.

Advantages and Limitations Compared to Conventional Methods

Advantages

- No chemical residues: UV-C leaves no residues, enabling production without preharvest intervals.

- No selective pressure: Pathogens do not develop resistance to the physical mode of action.
- Multifunctionality: Simultaneous effects on fungi, bacteria, and certain insect pests.
- Compatibility with organic farming and integrated pest management (IPM).
- High level of automation: Enables autonomous nighttime operation, reducing labor requirements.

Limitations and Constraints

- Lack of systemic effect: Acts only upon contact and requires repeated applications.
- Limited penetration: UV-C does not penetrate deep into the canopy; effectiveness depends on plant architecture.
- Phototoxicity risk: Overexposure may cause plant damage such as necrosis or bleaching.
- Operational logistics: Requires nighttime operation, energy supply, and adherence to safety protocols.

Commercial Viability and Future Potential

UV-C technologies are currently most widely adopted in high-intensity fruit and vegetable production systems with high market value. Business models such as "UV-as-a-Service" (e.g., TRIC, Saga) and proprietary equipment systems (e.g., CleanLight) provide diverse entry points for farms of varying sizes. The application of UV-C is particularly promising within the context of European policies aimed at pesticide reduction (e.g., the "Farm to Fork" strategy) and the development of more resilient agroecosystems. Rooted in the principles of photobiology and optoelectronics, this technology when effectively integrated with digital agro-platforms is emerging as a core component of the future paradigm of low-input, sustainable, and data-driven crop production.

Laser-Induced Breakdown Spectroscopy (LIBS)

Mechanism of Action and Scientific Basis

Laser-Induced Breakdown Spectroscopy (LIBS) is a high-resolution spectroanalytical technique in which a nanosecond or picosecond pulse from a high-energy laser (typically Nd:YAG, $\lambda = 1064$ nm) is focused onto the surface of a solid sample (e.g., dried and homogenized soil), causing localized ablation of the material and the generation of plasma within a microexplosion.

This plasma, heated to temperatures exceeding 10,000 K, emits spectrally distinct lines corresponding to the elemental composition of the sample. Through spectroscopic detection using a CCD-based system coupled with an echelle spectrometer, it is possible to simultaneously detect a broad range of elements across the spectrum (200–900 nm), including light elements such as carbon (C) and nitrogen (N), which are not detectable using conventional methods such as X-ray fluorescence (XRF).

A distinctive advantage of LIBS is its capacity for quasi-real-time analysis with minimal sample preparation simple drying and granulometric homogenization are sufficient. Averaging thousands of laser pulses per sample reduces variability and allows for reliable quantitative interpretation.

Using multivariate regression models (e.g., Partial Least Squares Regression PLSR, Principal Component Regression PCR) or machine learning approaches (e.g., support vector machines, convolutional neural networks), LIBS spectral data can be transformed into predictive models [2, 6] for agronomic parameters such as concentrations of macronutrients (K, Mg, Ca, P), micronutrients (Zn, Cu, Fe), total organic carbon (TOC), and soil texture. One of the main challenges is the so-called matrix effect the influence of the soil's physical and chemical properties on the intensity of emission lines which is addressed through complex calibration using a representative set of reference samples.

Practical Applications

Over the past decade, numerous validation studies have confirmed a strong correlation between LIBS-based predictions and standard laboratory methods such as ICP-OES, Kjeldahl, and Walkley-Black. For example, the portable Z-300 LIBS spectrometer (SciAps, USA) [11] achieved an $R^2 > 0.88$ when estimating total organic carbon (TOC) in soil samples from the United States and Canada, demonstrating high utility for assessing soil quality and organic fertilization needs. The most widely adopted system in practice is LaserAg (LogiAg, Canada) [8], where samples are compressed into pellets and analyzed with 3,000 laser pulses in just a few seconds. The system supports routine measurement of nutrients, pH, particle size distribution, and organic matter. Commercial laboratories such as Eurofins in Canada and Omnia in South Africa are already using LaserAg in operational settings. With an analysis time of less than five minutes per sample, the system enables high laboratory throughput and rapid feedback to users. In research contexts, efforts are underway to integrate LIBS sensors into field platforms (e.g., tractors, robots) to enable in-situ soil analysis during field operations. These sensors are expected to generate high-resolution spatial maps of soil nutrient levels (more than one sample per 10 m^2), which could significantly enhance the accuracy of variable-rate fertilization.

Companies Developing Solutions

Among the leading industrial players in LIBS technology for agronomic applications is the Canadian company LogiAg, which developed the comprehensive LaserAg laboratory system. This includes the quantum spectroscopic unit, integrated multivariate analytics software, and data interfaces for GIS platforms. LaserAg is designed as a high-throughput solution for commercial laboratories, enabling automated acquisition and interpretation of spectral data using thousands of laser pulses per sample. The U.S.-based company SciAps developed the portable LIBS unit Z-300, designed for rapid in-field diagnostics. The device supports assessment of parameters such as total organic carbon (TOC) and potentially macronutrients (P, K, Mg), with region-specific calibrations.

Due to its robustness and speed, the Z-300 is increasingly used in pilot projects focused on precision fertilization. Another notable company is Applied Spectra, which develops high-resolution laboratory LIBS systems with combined analysis capabilities (e.g., LA-ICP-MS) for complex, multipurpose research.

Their instruments are employed in environmental, agroecological, and soil science studies requiring high sensitivity and analytical resolution. On the research and development front, numerous institutions are actively contributing to the field, including the Institute of Soil Science at Zhejiang University (China), the University of São Paulo (Brazil), and Cornell University [5].

Their work supports the standardization of LIBS protocols, development of algorithms to correct for matrix effects, and integration of spectroscopic data with advanced artificial intelligence methods. Promising approaches include the development of portable units integrated with autonomous platforms for real-time soil mapping.

Advantages and Limitations Compared to Conventional Methods

Advantages

- Rapid analysis: Measurement time is less than 5 minutes per sample.
- Multi-element detection: Simultaneous quantification of macro- and microelements, including light elements.
- No chemicals or waste: Environm. friendly laboratory process without reagents.
- Minimal sample preparation: Eliminates time-consuming preparation steps.
- Field applicability: Potential for decentralized, in-field diagnostics using portable units.

Limitations and Constraints

- Calibration dependency: Requires region-specific models due to matrix effects.
- Limited sensitivity: Not comparable to ICP-MS for trace heavy metal detection.
- Interpretability of results: Often provides total elemental concentrations rather than extractable fractions.
- High equipment costs: Initial investment exceeds €50,000 for portable systems and €200,000 for laboratory-grade setups.

Commercial Viability and Future Potential

LIBS technology represents a critical component in the transition toward data-driven precision agriculture. Its capability for rapid, multi-element, reagent-free soil analysis aligns well with the ongoing digitalization of agroecosystems. Provided that instrumentation becomes more widely accessible, analytical precision improves, and standardized measurement protocols (e.g., ISO accreditation) are adopted, LIBS is likely to become an integral part of both laboratory-based and field-based agronomic diagnostics over the next decade. Thanks to its compatibility with geographic information systems (GIS), artificial intelligence algorithms, and autonomous platforms, LIBS is positioned as a promising solution for the advancement of regenerative and sustainable agriculture.

Comparison of Existing Photonic Technologies in Precision and Digital Agriculture

To provide a comprehensive overview of the comparative advantages and limitations of the discussed photonic technologies within the context of precision and sustainable agriculture, Table 1 presents a synthesized comparison.

It systematically outlines key technical parameters, agronomic performance capabilities, and the commercial maturity level of each technology. Additionally, information on leading technology providers and their application strategies is included to facilitate a better understanding of the relationship between innovative light-based approaches and conventional methods for crop protection and soil analytics.

Table 1. Comparative Overview of Photonic Technologies in Precision and Digital Agriculture

Technology	Leading Providers	Key Advantages	Key Limitations	Current Status and Accessibility
Laser-based weed control	Carbon Robotics (USA) LaserWeeder™. WeLASER (EU project) autonomous laser prototype for field crops. Startups and ongoing research (Germany, Netherlands)	Herbicide-free (suitable for organic farming). High precision; selectively targets weeds among crops. Reduces manual labor- Preserves soil structure. Avoids erosion.	High equipment cost. Slower coverage on large fields (currently suited for vegetables)- Technically demanding maintenance- Less effective on mature weeds	Commercially available for specialized crops (vegetables, horticulture). Primarily used in the U.S. EU projects in prototype stage. Early adopters report [illegible]80% reduction in weeding costs.
UV-C light for disease control	TRIC Robotics (USA). UV-C robots for strawberries (as-a-service). Saga Robotics (Norway/New Zealand). Thorvald UV robot for vineyards. CleanLight (Netherlands). Antobot + CleanLight (UK). compact UV robot for tunnels. Others in development (e.g. [illegible]aro X4)	Fungicide-free (no residues, no resistance development). Broad spectrum efficacy (fungi and some pests). No preharvest interval. suitable for organic farming. Automation allows nighttime operation	Frequent treatments required (e.g. weekly). Only effective at night (requires robotic platform). Limited light penetration (less effective in dense [illegible]). High initial equipment cost (robot or system)	Already in practical use: vineyards, berries (e.g., strawberries), and greenhouses. Commercially available as a service (TRIC) or equipment (CleanLight). Rapid adoption in high-value niche markets
LIBS soil analysis	[illegible]giAg LaserA[illegible]. (Canada). SciA[illegible] Z-[illegible] (USA)	Rapid multi-element analysis. Reagent-free (no chemical waste). High repeatability (less error in preparation). Portable field diagnostics possible	Requires region-specific calibrations (due to matrix effects). Limited sensitivity for trace elements. Results often reflect total rather than extractable content. High equipment cost.	Used in select laboratories. Handheld analyzers available only for experts, not yet routine but advancing rapidly broader adoption expected with growth of precision agriculture.

RESULTS AND DISCUSSION

A comprehensive review of current scientific and technical literature reveals that photonic technologies particularly UV-C illumination, laser-based weed control, and laser-induced breakdown spectroscopy (LIBS) constitute a technological foundation for the transition toward more precise, environmentally compatible, and data-driven agriculture. The reviewed studies consistently demonstrate that UV-C light effectively reduces fungal disease incidence across various horticultural crops (e.g., *Botrytis cinerea* in strawberries and grapes), with application efficacy strongly dependent on spectral intensity and temporal exposure dynamics. Systematic reviews also emphasize that UV-C treatments significantly reduce fungicide use, especially in organic production systems. For laser-based weed control, the literature confirms it as a highly precise method, particularly effective for selectively targeting weeds during early development stages. The technology shows strong potential for organic farming contexts where chemical weed control is not permitted, though it requires precise optoelectronic plant tracking and high-energy laser sources. Data from multiple reviews and meta-analyses [e.g., 16, 17] indicate that LIBS provides a multi-element, rapid, and reagent-free method for determining soil chemical composition. The strong correlation between LIBS outputs and standard chemical analyses (e.g., ICP-OES, TOC) demonstrates the method's value, particularly for precision fertilization and monitoring of soil resources. Key advantages also include compatibility with artificial intelligence algorithms and the potential for integration into autonomous field platforms. Based on the comparative synthesis, each technology demonstrates specific utility within distinct segments of agricultural practice:

- UV-C is optimal for intensive fruit and vegetable production systems.
- LIBS is most applicable in arable farming and sustainable agronomy, where rapid, spatially resolved soil data are essential.
- Laser-based weed control is emerging in organic farming systems as a high-tech alternative to herbicides.

The literature also highlights several challenges and limitations, including the energy demands of laser systems, the need for calibration models in LIBS, and regulatory considerations surrounding UV-C as a phytosanitary measure. A crucial factor for real-world implementation is user education and the availability of technical know-how, prompting authors to recommend the development of dedicated training programs. In conclusion, the reviewed photonic technologies form a synergistic ensemble that not only complement existing methods but also enables a transformation of agriculture toward greater precision, reduced environmental impact, and enhanced responsiveness to agroecological dynamics. Continued research, validation across diverse agroclimatic regions, and the standardization of measurement protocols will be key to their long-term adoption.

CONCLUSIONS

This study provides a comprehensive examination of advanced photonic technologies and their current and potential applications within precision and digital agriculture.

By analyzing three core technologies laser-based targeted weed control, ultraviolet-C (UV-C) radiation for plant disease suppression, and laser-induced breakdown spectroscopy (LIBS) for soil analysis the research outlines both the scientific mechanisms underpinning these approaches and their agronomic relevance. Findings from peer-reviewed studies and field validations confirm that photonic systems offer substantial advantages in terms of spatial selectivity, chemical-free operation, and automation readiness. UV-C light has demonstrated consistent efficacy in suppressing fungal pathogens across various high-value horticultural crops, with significant reductions in fungicide usage, particularly in organic systems. Laser weeding has proven to be a highly accurate method for non-contact weed removal, especially in early developmental stages, with applications particularly suited to organic horticulture.

LIBS, on the other hand, enables rapid, multi-element, and reagent-free soil diagnostics, providing actionable insights for nutrient management and supporting the principles of site-specific fertilization. Despite their promise, each technology is associated with specific operational and technical challenges: laser systems are capital-intensive and require optoelectronic precision, UV-C treatments must be timed to avoid pathogen photorepair mechanisms, and LIBS depends on complex calibration models to mitigate matrix effects. Furthermore, regulatory, economic, and knowledge transfer barriers remain significant factors influencing adoption rates (7). Nevertheless, these technologies collectively form a synergistic toolkit that aligns with global sustainability goals, offering pathways to reduce chemical inputs, enhance resource use efficiency, and improve resilience in agroecosystems. Their integration into digital agricultural frameworks alongside artificial intelligence, GIS systems, and autonomous platforms marks a pivotal step toward next-generation farming systems.

The continued development and deployment of these photonic solutions will require targeted research, robust validation across agroclimatic zones, standardization of protocols, and dedicated training for end-users. As such, photonics holds the potential not only to augment but to fundamentally transform how we monitor, manage, and optimize crop production in an era increasingly defined by ecological constraints and technological possibilities.

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NAPREDNE FOTONSKE TEHNOLOGIJE U PRECIZNOJ I DIGITALNOJ POLJOPRIVREDI

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Apstrakt: Tehnologije zasnovane na fotonima, na kontrolisanoj primeni svetlosne energije, postaju ključna komponenta moderne digitalne i precizne poljoprivrede.
Ovaj članak prikazuje tri komplementarna pristupa: ciljano suzbijanje korova zasnovano na laserima, UV-C svetlost za suzbijanje gljivičnih bolesti i laserski indukovana spektroskopija razgradnje -LIBS, za analizu zemljišta.
Svaka od ovih tehnologija (metoda) nudi visoku prostornu i spektralnu selektivnost, potencijal automatizacije i mogućnost smanjenja oslanjanja na hemijske agense i konvencionalnu laboratorijsku dijagnostiku.
Predstavljene su naučne osnove svakog pristupa, trenutne primene, agronomski efekti i tehnički izazovi, i analiza njihove potencijalne integracije u šire agro-digitalne sisteme. Poseban naglasak je stavljen na ulogu fotonike u prelasku ka ekološki odgovornoj, niskoinvesticionoj i podacima vođenoj proizvodnji hrane.

Ovaj doprinos pruža osnovu za dalja istraživanja i praktičnu primenu ovih tehnologija u različitim modelima proizvodnje useva.

Ključne reči: *Fotonika, suzbijanje korova pomoću lasera, UV-C zračenje, LIBS, analiza zemljišta, precizna poljoprivreda, digitalizacija poljoprivrede, agrooptičke tehnologije.*

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