

Trends in the postharvest treatment and handling of agricultural products: A Review and analysis

Tendencias en el manejo y tratamiento poscosecha de productos agrícolas: Revisión y análisis

 Carlos Modesto Martínez Hernández*

Universidad Central "Marta Abreu" de las Villas, Santa Clara, Villa Clara, Cuba.

*Author for correspondence: Carlos Modesto Martínez-Hernández, e-mail: carlosmh@uclv.edu.cu

ABSTRACT: This work was developed considering the rise of new scientific information technologies and artificial intelligence (AI) at both the international and national levels. These technologies utilize software, sensors, and next-generation non-destructive measuring instruments as tools, and are related to reducing environmental pollution and improving the quality and traceability of agricultural production. Starting from the problem of the widespread use of destructive methods for analyzing post-harvest variables in agricultural products, a literature review was undertaken to identify international trends in this field, which was the primary objective of this study. The work is structured in three parts: first, the trends and methods for the handling, treatment, and use of agricultural products are described. Second, the specifics of using and implementing these treatments are addressed. Finally, their potential application in the Cuban context is analyzed. In conclusion, the current and future state of the art in post-harvest handling and treatment trends for agricultural products is presented, along with their advantages and limitations.

Keywords: Artificial intelligence (AI), non-destructive sensors and measuring instruments, traceability, post-harvest handling.

RESUMEN: Teniendo en cuenta el auge de las nuevas tecnologías de la información científica y la inteligencia artificial (IA) a escala internacional y nacional, los cuales utilizan como herramientas softwares, sensores e instrumentos de medición de nueva generación no destructivos, así como aspectos relacionados con la disminución de la contaminación medioambiental, calidad y trazabilidad de las producciones agrícolas se desarrolló este trabajo. Partiendo de la problemática del uso masivo de los métodos destructivos de análisis de las variables poscosecha de productos agrícolas, se acometió una revisión bibliográfica para conocer cuáles tendencias internacionales se presentarán en este campo, siendo este particular el objetivo del mismo. El trabajo se estructuró en tres partes: primeramente, se describen las tendencias y los métodos para la manipulación, tratamiento y utilización de los productos agrícolas. Posteriormente se abordan las particularidades para utilizar y llevar a cabo estos tratamientos. Finalmente, se analiza su posible utilización en el caso cubano. Como conclusión, se muestra el estado del arte en las tendencias del manejo y tratamiento poscosecha de productos agrícolas en la actualidad y a futuro, sus ventajas y limitaciones.

Palabras clave: inteligencia artificial (IA), sensores e instrumentos de medición no destructivos, trazabilidad, manejo poscosecha.

INTRODUCTION

According to Kader (2002) and Thompson (2015), global agriculture faces one of its greatest challenges: feeding a population projected to reach 10 billion by 2050, while simultaneously grappling with resource constraints, climate change, and high levels of food waste. According to the FAO, approximately 14% of food is lost between harvest and retail, a percentage that increases dramatically in developing regions and for perishable products.

The post-harvest stage represents a critical link where significant economic losses and a reduction in nutritional quality are concentrated. Simultaneously, consumers are increasingly demanding transparency and traceability

regarding the origin, production conditions, and handling of their food, driven by concerns about food safety, sustainability, and authenticity. (Dentoni, 2021).

The convergence of digital technologies is radically transforming agricultural management. Agriculture 4.0 integrates IoT sensors, drones, satellites, artificial intelligence, and big data to create more efficient, resilient, and transparent agri-food systems.

The agricultural and agro-industrial sector is undergoing a fundamental transformation in its quality control and product evaluation methods. Historically, destructive methods (random sampling followed by laboratory analysis) have dominated due to their analytical precision. However, they present critical limitations such as:

Received: 15/11/2025

Accepted: 28/03/2026

Conflict of interest: The author of this work declares no conflict of interest.

Author contributions: Conceptualization, Data curation, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing: Carlos Modesto Martínez Hernández.

The mention of specific brands of equipment, instruments, or materials is for identification purposes only and does not constitute any promotional endorsement by either the author or the publisher.



This is an open access article under terms of the license Creative Commons Attribution-NonCommercial (BY-NC 4.0).
<https://creativecommons.org/licenses/by-nc/4.0/>



- Limited representativeness (generally <1% of production);
- Loss of product and economic value;
- Delayed feedback in the production chain;
- Inability to continuously evaluate.

The new paradigm seeks to implement 100% non-destructive inspection systems that allow for:

- Real-time evaluation on processing lines;
- Comprehensive quality control of the entire production process;
- Preservation of the product's commercial value;
- Complete traceability of quality attributes.

According to Valente (2021), agriculture is undergoing an unprecedented technological transformation. Driven by the need for greater efficiency, sustainability, and profitability, the democratization of advanced tools is enabling historically marginalized actors, such as medium-sized farmers and cooperatives, to access capabilities that were previously the exclusive domain of large corporations. Two fundamental pillars of this revolution have undoubtedly been the miniaturization and cost reduction of portable sensors and spectrometers, as well as the increasing accessibility of agricultural robotics. The confluence of factors such as the structural labor shortage, which in the European Union (EU) has meant the loss of 2.5 million workers in a decade, and the technological maturity of artificial intelligence (AI), computer vision, and connectivity, has created the perfect breeding ground for this transition. The result is an ecosystem where decision-making is based on real-time data, collected on-site with affordable devices, and where repetitive and critical tasks such as harvesting are beginning to be automated cost-effectively.

According to Pritt & Chern (2017); Kussul (2022), we are living through a turning point in industrial history. If the first industrial revolution gave us the steam engine, and the third automation and electronics, today we are witnessing the birth of a fourth revolution where value is no longer created solely with steel and gears, but with data, algorithms, and real-time decisions.

Given these perspectives, this work aimed to investigate current and future trends in methods and technologies for analyzing post-harvest variables in agricultural products.

DEVELOPMENT

This study began with keywords related to the topic of study (trends in the post-harvest handling and treatment of agricultural products), as well as internet searches using specialized platforms and artificial intelligence. This allowed for the analysis of various concepts, including IoT technologies in agriculture, drones, remote sensing and satellites, post-harvest handling, and traceability, among others. As a result of the search on these topics, scientific articles published between 2019 and 2025 in journals such as *Computers and Electronics in Agriculture* (Elsevier); *Biosystems Engineering* (Elsevier); *Precision*

Agriculture (Springer); *Remote Sensing* (MDPI); *IEEE Transactions on AgriFood Electronics*; *Postharvest Biology and Technology* (Elsevier); and *Food Control* (Elsevier) were consulted.

Technical reports and guides, government agencies, consortia and associations, online resources and platforms, technical standards, research databases, and training courses and programs were also consulted. Motivated by the vast amount of information analyzed, the results obtained have been presented by addressing aspects such as: types, device characteristics, advantages, applications, international regulations and standards, technical limitations, current limitations and technological challenges, barriers to mass adoption, active research areas, success stories and commercial applications, implemented industrial examples, and future perspectives. This approach allows for comparison and evaluation.

According to Ferrández (2022); Ruiz (2022); Chen (2023); Kamilaris (2023); Zhang (2023); Mukhopadhyay & Postolache (2021), the Internet of Things (IoT) for agriculture comprises four essential components:

- Sensor devices: These convert physical, chemical, and biological parameters into electrical signals;
- Sensor devices: These convert physical, chemical, and biological parameters into electrical signals; Connectivity: Communication protocols (LoRaWAN, Sigfox, NB-IoT, WiFi, 5G);
- Processing platform: Data storage, analysis, and visualization;
- User interface: Dashboards, alerts, automated control systems.

In the case of post-harvest, there are some specificities which can be classified as: Sensors for Environmental Conditions in Storage

Temperature sensors: Thermistors, RTDs, thermocouples, infrared sensors;

Typical range: -40°C to +85°C;

Accuracy: ±0.1°C to ±0.5°C;

Strategic placement: critical points in cold storage rooms;

Relative humidity sensors: Capacitive, resistive, dew point;

Range: 0-100% RH;

Accuracy: ±1.5% to ±3.5%;

Application: prevention of condensation and mold growth;

Controlled/modified atmosphere sensors:

- O₂ concentration: Electrochemical and optical sensors (0-25%);
- CO₂ concentration: NDIR and chemical sensors (0-20%);
- Ethylene concentration: Photoacoustic and electrochemical sensors (ppb to ppm);
- Air quality sensors: VOCs, ammonia, hydrogen sulfide;

Product Quality and Condition Sensors

Firmness sensors: Non-destructive force/pressure sensors;

Portable spectral sensors: NIR, VIS-NIR for soluble solids, acidity, and maturity;

Chlorophyll fluorescence sensors: Indicators of physiological stress;

Biosensors: Detection of pathogens (*E. coli*, *Salmonella*, *Listeria*);

Electronic nose and tongue sensors: Volatile and flavor profiles.

Logistics Monitoring Sensors

Impact and vibration sensors: Triaxial accelerometers;

Tilt sensors: For monitoring load orientation;

Light sensors: Detection of container opening;

GPS/GNSS Sensors: Real-time location.

Sensors for Smart Packaging

Time-Temperature Indicators (TTI);

Freshness Indicators: pH sensors, specific gases;

Active and semi-active RFID/NFC;

LoRa/LoRaWAN: Range 5-15 km in rural areas, low power, low cost;

Sigfox: Range 10-40 km, very small messages;

NB-IoT: Over cellular infrastructure, higher bandwidth.

IoT Satellite Communications:

- For remote areas without terrestrial coverage;
- Providers: Iridium, Orbcomm, Swarm Technologies.

Specialized IoT Platforms

General purpose: AWS IoT, Microsoft Azure IoT, Google Cloud IoT;

Specialized for agriculture: Arable, Pessl Instruments, CropX;

Open-source platforms: ThingsBoard, Node-RED, Home Assistant.

Regarding the topic of drones in agriculture, there is a wide variety of information sources that address different types and uses. Among the authors who have addressed this topic, the following were consulted [García *et al.* \(2021\)](#); [Jafarbiglu & Pourreza \(2022\)](#); [Tripicchio \(2022\)](#); [Zhang \(2022\)](#); [Thenkabail & Lyon \(2023\)](#).

Drones (UAVs) in Post-Harvest Management

Specific Types and Configurations

Multirotor Drones (Multicopters);

Advantages: Hovering, vertical take-off and landing (VTOL);

Configurations: Quadcopters, hexacopters, octocopters;

Payload capacity: 0.5-10 kg;

Flight time: 15-40 minutes;

Applications: Detailed inspection, warehouse interiors

Fixed-Wing Drones

Advantages: Longer flight time, wider coverage;

Autonomy: 1-3 hours;

Speed: 50-100 km/h;

Applications: Monitoring of large facilities, storage yards.

Hybrid Drones (VTOL + Fixed Wing)

Combination of advantages: vertical takeoff + flight efficiency;

Emerging applications in agricultural logistics;

Specialized Onboard Sensors.

Multispectral Cameras

Typical bands: Green (550 nm), Red (660 nm), Red Edge (735 nm), NIR (790 nm);

Derived indices:

- NDVI (Normalized Difference Vegetation Index): Plant health;
- NDRE (Normalized Difference Red Edge): Chlorophyll content;
- GNDVI (Green NDVI): Early stress;
- Resolution: 2-20 MP;

Post-harvest applications: Detection of mechanical damage and physiological disorders.

Thermal Cameras

Spectral range: 7.5-13.5 μm (thermal infrared);

Thermal resolution: $<0.05^\circ\text{C}$;

Applications:

- Detection of hot spots in storage;
- Leaks in refrigeration systems;
- Thermal mapping of facilities.

Hyperspectral Cameras

- Spectral bands: 100-300 contiguous bands;
- Range: 400-1000 nm (VNIR) or 900-2500 nm (SWIR);

Advanced applications:

- Detection of early spoilage;
- Grading by quality/maturity;
- Identification of contaminants.

LiDAR (Light Detection and Ranging) Sensors

Principle: Distance measurement using laser pulses;

Post-harvest applications:

- 3D modeling of facilities;
- Measurement of storage volumes;
- Structural inspection of infrastructure.

High-Resolution RGB Cameras

- Resolution: 20-45 MP;

Applications:

- Detailed visual inspection;
- Automated QR code/label reading;
- Condition documentation.

Post-Harvest Operational Applications:

- Infrastructure Inspection and Maintenance;
- Thermal mapping of cold storage rooms;

- Detection of inadequate insulation;
- Inspection of ventilation/refrigeration systems.

External Storage Condition Monitoring:

- Storage yards: detection of moisture accumulation and pests;
- Silos and warehouses: structural integrity assessment;

Inventory Management:

- Automated counting of pallets, boxes, and containers;
- Verification of locations in storage yards.

Quality Control:

- Early detection of rot and damage;
- Sorting by size, color, and defects in stored batches.

Security and Surveillance:

- Perimeter monitoring of facilities;
- Intrusion and theft detection. Satellites for agricultural monitoring and logistics. According to Lambert (2022) satellites can be used in various activities, including agricultural and logistics monitoring. Some examples are shown below.

Earth Observation Satellites

Medium-High Resolution Satellites (10-30 m):

- Sentinel-2 (ESA Copernicus):
- Resolution: 10 m (4 bands), 20 m (6 bands), 60 m (3 bands);
- Time span: 5 days (2 satellites);
- Features: Free, 13 spectral bands;

Landsat 8 & 9 (NASA/USGS):

- Resolution: 15 m (pan), 30 m (multispectral);
- Time span: 16 days;
- Features: Historical since 1972, 11 bands.

Radar Satellites (SAR)

- Sentinel-1 (ESA): Synthetic Aperture Radar (C-band);
- Advantage: Cloud-penetrating, operates day/night;
- Applications: Monitoring soil moisture, ground deformation;
- SAOCOM (Argentina): L-band SAR;
- Specialized in soil moisture.

Integrated Traceability Systems

Regarding traceability, Weiss (2023), addresses the use of sensors to track the traceability chain in agricultural products. Furthermore, Dentoni (2021) outlines some of the fundamentals of agri-food traceability:

Fundamentals of Agri-food Traceability

Traceability: The ability to track the movement of a food product through specified stages of production, processing, and distribution (Codex Alimentarius);

Backward Traceability: Origin of inputs;

Internal Traceability: Processes within the organization;

Forward Traceability: Destination of products.

International Regulations and Standards:

- GS1: Global identification standards (GTIN, GLN, SSCC);
- ISO 22005:2007: Traceability in the food chain;
- FSMA (FDA): Food Safety Modernization Act (USA);
- Regulation (EU) 178/2002: General principles of traceability in the EU;
- GlobalG.A.P.: Good Agricultural Practices.

Integration of Technologies for End-to-End Traceability

Stage 1: Production and Harvesting

Satellites: Location verification, crop conditions;

Drones: Maturity monitoring, harvest estimation;

IoT: Environmental conditions in the field, practice records.

Stage 2: Initial Transport and Reception

IoT: Sensors in vehicles (temperature, humidity, impacts);

GPS/GLONASS: Real-time location tracking;

RFID: Automatic identification upon receiving.

Stage 3: Processing and Storage

IoT: Environmental sensor network in facilities;

Drones: Facility inspection, inventory;

Computer vision: Automated quality control;

Blockchain: Unalterable record of batches and conditions;

Stage 4: Distribution and Secondary Transport

IoT: Monitors in containers/vehicles;

Opening sensors: Seal integrity;

Logistics platforms: Route optimization.

Stage 5: Retail and Consumer

QR/NFC: Consumer access to traceability information;

Mobile apps: Authenticity verification, history;

Sensors on shelves: Monitoring of conditions at the point of sale.

Technical Limitations

IoT Sensors:

- Battery life in remote locations;
- Interference in wireless communications;
- Sensor calibration and maintenance;
- Integration of heterogeneous systems.

Drones:

- Regulatory limitations (airspace, altitude, BVLOS);
- Limited autonomy (especially with heavy sensors);
- Adverse weather conditions;
- Processing of large volumes of data.

Satellites:

- Limited spatial/temporal resolution;
- Clouds that block optical sensors;
- Data availability latency;
- Complex data interpretation.

Furthermore, according to Thompson (2015); Thenkabail (2021); Petropoulos & Srivastava (2023), the dominant technologies in the new generation of sensors include:

Hyperspectral and multispectral near-infrared spectroscopy (NIRS):

- Fundamental advancement: From spot spectra to spectral images;
- Traditional NIRS: Provides an average spectrum of a small area;
- Hyperspectral NIRS: Captures images with hundreds of continuous spectral bands;
- Multispectral NIRS: Uses strategically selected spectral bands.

Revolutionary applications:

- Compound distribution mapping: Spatial visualization of sugars, moisture, acidity, and phenolic compounds;
- Internal defect detection: Brown spots, freezing damage, and glassiness;
- Internal quality grading: Differentiation of fruit based on chemical parameters;
- Shelf-life prediction: Modeling of ripening and deterioration.

Operational advantages:

- Speed: Up to 10-20 fruits/second on grading lines;
- Accuracy: $R^2 > 0.90$ for soluble solids in fruits such as apples and grapes;
- Integration: Compatible with existing sorting systems;
- Contactless: Eliminates cross-contamination.

Thermal and Fluorescence Imaging:

- Agricultural Thermography: Beyond Surface Temperature;
- Physical Principle: Detects infrared emission (8-14 μm) related to temperature and physiological properties;
- Thermal Resolution: $<0.1^\circ\text{C}$ in advanced systems;

Applications in Crops:

- Early Water Stress: Detection before visible symptoms through canopy temperature analysis;

- Disease Detection: Abnormal thermal patterns due to pathogen metabolic activity;
- Assessment of Chilling Injury: Changes in stomatal conductance and transpiration;
- Irrigation Optimization: Zoning of water requirements within the field;
- Chlorophyll Fluorescence Imaging:
- Kautsky Induction: Measures photosynthetic efficiency (Fv/Fm) as an indicator of stress;
- Multicolor Fluorescence: Differentiates types of stress (nutritional, water, pathological);
- Ultra-early detection: Up to 5-7 days before visible symptoms of infection.

Portable magnetic resonance imaging (MRI) and computed tomography (CT):

- Miniaturization of medical technology for the agricultural industry;
- Low-field systems: 0.1-0.5 Tesla (vs. 1.5-3T medical);
- Specialized geometries: Designed for specific agricultural products;
- Decreasing costs: From $>€500,000$ to $<€100,000$ for specialized systems;
- Applications in high-value fruits;
- Non-destructive internal visualization: Holes, hail damage, internal rot;
- Texture analysis: Air space distribution, tissue density;
- Ripening studies: Structural changes during storage;
- Parental selection: In genetic improvement programs;

Agricultural CT (Low-energy X-ray):

- Submillimeter resolution: Detection of pits in shelled fruit, insects in grains;
- 3D analysis: Reconstruction of complex internal structures;
- Food safety: Detection of non-metallic foreign bodies.

Inspection Robotics with Optical Feedback:

- Distributed Force Sensors: Tactile arrays with spatial resolution;
- Adaptive Actuation: Robotic arms that adjust pressure based on product response;
- Machine Learning: Correlation between mechanical responses and quality attributes;

Measurable Parameters:

- Objective Firmness: Force-deformation curves with $>95\%$ accuracy vs. penetrometer;

- Elasticity/Viscosity: Rheological properties through dynamic testing;
- Texture Homogeneity: Detection of locally soft/hard areas;
- Maturity Classification: Based on evolving mechanical properties;

Non-Destructive Impact Systems:

- Acoustic Response Analysis: Characteristic frequencies related to firmness;
- Acceleration Sensors: Deceleration patterns during controlled impact;
- Online Application: Up to 30-40 measurements/second in industrial systems.

Technological Integration and Converging Trends: Sensor Fusion:

- NIRS + Touch Combination: Chemical and mechanical attributes in a single measurement;
- Thermal + Fluorescence: Comprehensive diagnosis of physiological state;
- MRI/CT + Spectroscopy: Correlation of internal structure and chemical composition.

Artificial Intelligence and Big Data:

- Convolutional Neural Networks: For hyperspectral image analysis;
- Multivariate Predictive Models: PLS, SVM, Random Forest for calibration;
- Recommendation Systems: Management suggestions based on sensory data.

Miniaturization and Democratization:

- Sensors in Smartphones: Portable NIR spectrometers for <€5,000;
- Equipped Drones: Precision aerial thermography and fluorescence;
- IoT Systems: Distributed sensor networks in the field and post-harvest.

Current limitations and technological challenges:

Barriers to mass adoption:

- Initial cost: Although decreasing, still significant for small producers;
- Calibration complexity: Requires representative sampling and maintenance;
- Speed vs. Accuracy: A trade-off in high-speed systems;
- Natural variability: Adaptation to differences between crops, varieties, and conditions;
- Data infrastructure: Need for robust connectivity and processing.

Active Research Areas:

- Reducing Acquisition Time: Spectral Compression Techniques;
- Standardizing Protocols: Metrology for Precision Agriculture;
- Multi-Source Data Fusion: Satellite/Drone/Ground Integration;
- Interpretable Physical Models: Beyond AI "Black Boxes"

Success Stories and Commercial Applications:

Implemented Industrial Examples:

- Apple Sweetness Grading: Hyperspectral NIRS Systems on Packing Lines (European Union, USA);
- Citrus Freeze Damage Detection: Thermography + NIR (Spain, Israel);
- Avocado Maturity Selection: Portable MRI for High-Value Markets (Mexico, Peru);
- Harvesting Robots with Haptic Feedback: For Delicate Fruits (Japan, Netherlands);

Documented ROI:

- Loss Reduction: 15-30% in Perishable Fruits;
- Product value increase: 20-50% through Premium classification;
- Labor savings: 40-70% in inspection tasks;
- Resource optimization: 10-25% in water, fertilizers, and energy.

Future outlook (2025-2035):

Emerging trends:

- Quantum sensors: Terahertz spectroscopy for molecular analysis;
- Implantable nanosensors: For continuous monitoring within plants
- Augmented reality: Overlaying sensor data in the field;
- Quality blockchain: Immutable record of measured attributes;

Expected scalability:

- Additional cost reduction: 30-50% in the next 5 years;
- Complete automation: Self-calibrating and self-diagnostic systems;
- Vertical integration: From field to consumer with continuous data;
- Global democratization: Access for small and medium-sized producers.

Today there is a wide range of portable, affordable and easy-to-use devices, among which we can mention:

- Chlorophyll and Greenness Measurement: Devices such as portable chlorophyll meters (e.g., SPAD range 0.0-99.9) allow for the assessment of a plant's nutritional and health status, directly correlating with its photosynthetic potential and yield. These tools provide readings in under 3 seconds and are compact enough for daily use in the field.
- Soluble Solids Analysis (°Brix): Refractometers, optical instruments for measuring sugars, are essential for determining the optimal harvest time for fruits and vegetables. Portable digital models have greatly simplified this task, offering automatic temperature compensation and accuracy comparable to laboratory equipment, but at a significantly lower cost and with a much shorter learning curve.
- Comprehensive Soil and Sap Analysis: Portable kits allow for the simultaneous measurement of multiple parameters. One example is the LAQUAtwin sensor kit, which can measure pH, electrical conductivity (EC), nitrates (NO₃), calcium (Ca), potassium (K), and sodium (Na) in sap extracts or soil, with 90-95% accuracy compared to ion chromatography. This empowers farmers to become their own plant nutrition analysts.

Agricultural robotics is transitioning from a futuristic and expensive concept to a practical solution for pressing problems. Its adoption is no longer in question; the focus is now on how and when to integrate it cost-effectively. The deployment of robots is being accelerated by a perfect storm of factors:

- Labor crisis: The scarcity and rising cost of labor, which can represent up to 38% of fruit production costs, make automation an economic necessity, not just a technological option.
- Labor crisis: The scarcity and rising cost of labor, which can represent up to 38% of production costs in fruit orchards, make automation an economic necessity, not just a technological option.
- Enabling technological maturity: The combination of machine vision with AI, advanced sensors (LiDAR, multispectral), and autonomous navigation systems (centimeter-level RTK GNSS) has resolved the main technical challenges of operating in complex and unstructured agricultural environments.
- Business models and cost reduction: Larger-scale manufacturing, competition among suppliers, and the emergence of Robots as a Service (RaaS) models are lowering the capital barrier to entry. Projections indicate that robotics can reduce harvesting costs by 30% to 50%.

According to [Tramallino & Zeni \(2024\)](#), the advancement of artificial intelligence (AI) and machine learning is characterized by:

- AI as the brain of the data ecosystem within the following context:
- The proliferation of sensors (IoT) generates massive volumes of data;
- Data without intelligent processing is merely "noise";

AI as the central nervous system:

- Integrates heterogeneous data;
- Learns complex patterns;
- Makes autonomous decisions.

These systems have countless applications in industry and agriculture, such as:

- Predictive maintenance in wind turbines using vibration data and hybrid models;
- Detection of defects imperceptible to the human eye;
- Quality control: Detection of cracks in castings;
- Predicting failures before they occur;
- Detection of defects in internal layers, among others.

In summary: this work has shown that the predominant trends in methods and technologies for the analysis of post-harvest variables of agricultural products are related to the use of: Internet of Things (IoT), Sensors, Drones, IoT Satellite Communications and Specialized IoT Platforms.

Analysis

In Cuba, to date, very few of these technologies are used at the field level; however, initial steps are being taken in research projects, as well as in some universities and research centers. In this regard, remote sensing of soil salinity [García *et al.* \(2021\)](#), soil moisture, nutrient potential of different soils and crops, and impact damage to agricultural products have been studied in recent years using various techniques, such as VIS-NIR, by different authors. Currently, the use of drones for fertilizer application and the introduction of solar panels for irrigation and drying of agricultural products are some of the current trends in Cuba. Regarding new technologies for the post-harvest handling and treatment of agricultural products, the literature on this topic is primarily international, with few bibliographic references from our country contributing to the analysis in this work. It should be noted that these technologies can be considered mature, while in other cases, they are still developing. However, in our opinion, the limiting factor in this regard is their high price or cost. Whenever the introduction of any of these technologies is considered, the first step should be an economic feasibility analysis to determine in which contexts they can be used immediately and in which they cannot.

The development of each of these post-harvest handling and treatment techniques for agricultural products is based on national and international protocols and standards,

which are strictly enforced according to the laws of each country. However, it is necessary to have sufficient training and equipment to determine which technique is most appropriate. In the Cuban case, this is both possible and feasible, as both of these prerequisites are met.

As can be seen in current and future conditions, a wide range of possibilities for measuring, monitoring, controlling, and tracing harvested and unharvested agricultural products are emerging daily. Hence the importance of staying informed and prepared for the application of all or some of these technologies, depending on the objective economic and financial conditions of each country for their implementation. In the author's opinion, the fundamental strength of this research lies in providing researchers and producers involved in the post-harvest handling and treatment of agricultural products with a compendium of the main current and future methods and technologies necessary for research and the application of results at the production level, within the framework of their technological and financial capabilities.

CONCLUSIONS

The miniaturization and democratization of technology is reshaping the agricultural landscape, bringing precision agriculture tools to a much broader base of producers. Portable spectrometers and sensors have transformed the accurate measurement of key parameters into a fast, cost-effective, and on-the-ground routine, displacing traditional laboratories for numerous applications. Simultaneously, agricultural robotics is moving beyond the pilot phase to establish itself as a tangible and increasingly accessible solution to the challenges of labor costs, quality, and traceability. The synergy between the Internet of Things (IoT), artificial intelligence (AI), and real-time computing is not a future trend, but a current operational reality. The integration of these technologies is creating industrial ecosystems where:

- Sensors are the senses that capture physical reality.
- Artificial intelligence (AI) is the brain that interprets and understands.
- Predictive models are the intuition that anticipates.

Real-time calibration is the continuous learning that adapts. The tools and algorithms are available, accessible, and proven.

The transition to 100% non-destructive sensing systems represents a paradigm shift with profound implications:

- Economic: Maximizing value and reducing losses;
- Environmental: Optimizing inputs and promoting sustainability;
- Social: Traceability and transparency for consumers;
- Scientific: New understanding of biological processes.

The technologies described (hyperspectral NIRS, thermography, portable MRI/CT, tactile sensors) are not futuristic technologies, but implemented realities that are being refined and democratized. Their convergence with artificial intelligence (AI), robotics, and data science is creating a precision agriculture ecosystem that will radically transform how we produce, process, and ensure food quality.

The future is non-destructive, quantitative, and comprehensive. The ability to "see the invisible" and "measure without touching" is redefining quality and efficiency standards in the global agri-food chain.

REFERENCES

- CHEN, Y.: "A comprehensive review of IoT-based monitoring systems for postharvest quality management", *Computers and Electronics in Agriculture*, 205: 107584, 2023.
- DENTONI, D.: "Blockchain and Other Emerging Technologies for Food Traceability", *Revista Internacional Administración & Finanzas*, 7(5): 61-76., 2021.
- FERRÁNDEZ, F.J.: *IoT and Smart Technologies for Sustainable Agriculture*, MDPI Books ed., 2022.
- GARCÍA, R.A.; POSADA, M.D.G.; TORRES, K.; VILLAZÓN, J.A.; ABELLÓN, M.I.; VELÁZQUEZ, E.C.: "Remote Sensing of Salinity in Agroecosystem of Mayarí, at Holguín Province, Cuba", *Revista Ciencias Técnicas Agropecuarias*, 30(1): 26-32, 2021, ISSN: 1010-2760.
- JAFARBIGLU, H.; POURREZA, A.: *Unmanned Aerial Systems in Precision Agriculture*, Ed. Elsevier., 2022.
- KADER, A.A.: *Postharvest technology of horticultural crops.*, 2002, ISBN: 1-879906-51-1.
- KAMILARIS, A.: "A review of the combination of IoT, blockchain and AI for sustainable food supply chains", *IEEE Internet of Things Journal*, 10(5): 3871-3890, 2023.
- KUSSUL, N.: *Deep Learning for Satellite Image Analysis*, Springer, 2022.
- LAMBERT, M.J.: "Satellite-based verification of geographical origin for high-value agricultural products", *Food Control*, 133: 108621, 2022.
- MUKHOPADHYAY, S.C.; POSTOLACHE, O.A.: *Internet of Things for Agricultural Applications*, Springer, 2021.
- PETROPOULOS, G.P.; SRIVASTAVA, P.K.: *Satellite Remote Sensing of Agricultural Land*, Elsevier, 2023.
- PRITT, M.; CHERN, G.: "Satellite image classification with deep learning", En: *2017 IEEE applied imagery pattern recognition workshop (AIPR)*, Ed. IEEE, pp. 1-7, 2017, ISBN: 1-5386-1235-6.
- RUIZ, L.: "Low-cost IoT-based sensor system for real-time monitoring of fruit cold chain", *IEEE Sensors Journal*, 22(5): 4223-4232, 2022.
- THENKABAIL, P.S.: *Remote Sensing of Agriculture and Land Cover/Land Use Changes*, CRC Press, 2021.

- THENKABAIL, P.S.; LYON, J.G.: *Drone Technology in Agriculture: Principles and Applications*, CRC Press, 2023.
- THOMPSON, A.K.: *Fruit and vegetable storage: hypobaric, hyperbaric and controlled atmosphere*, Ed. Springer, 2015, ISBN: 3-319-23591-5.
- TRAMALLINO, C.P.; ZENI, A.M.: “Avances y discusiones sobre el uso de inteligencia artificial (IA) en educación”, *Educación*, 33(64): 29-54, 2024.
- TRIPICCHIO, P.: “Towards smart farming and sustainable agriculture with drones”, *IEEE Transactions on Instrumentation and Measurement*, ser. IoT and AI, 71: 1-11, 2022.
- VALENTE, J.: *Robotics and Automation for Improving Agriculture*, Burleigh Dodds Science Publishing, 2021.
- WEISS, M.: “Remote sensing for agricultural supply chain traceability: A review”, *Remote Sensing of Environment*, 284: 113338, 2023.
- ZHANG, C.: “Automatic detection of postharvest fruit defects using drone-based multispectral imaging”, *Precision Agriculture*, 23(3): 987-1005, 2022.
- ZHANG, Q.: *Internet of Things for Smart Agriculture: Technologies and Applications*, Springer, 2023.