Digital and Industry 4.0 technologies in olive farming and industry

recent applications and future outlook

Parra-López, Carlos; Ben Abdallah, Saker; Hassoun, Abdo; Jagtap, Sandeep; Garcia-Garcia, Guillermo; Hassen, Tarek Ben; Trollman, Hana; Trollman, Frank; Carmona-Torres, Carmen

Published in:
Smart Agricultural Technology

DOI:
10.1016/j.atech.2025.101376

2025

Document Version:
Publisher's PDF, also known as Version of record

Smart Agricultural Technology 12 (2025) 101376

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Digital and Industry 4.0 technologies in olive farming and industry: Recent applications and future outlook

Carlos Parra-López [a], Saker Ben Abdallah [b], Abdo Hassoun [c,d], Sandeep Jagtap [e,f,*], Guillermo Garcia-Garcia [g], Tarek Ben Hassen [h], Hana Trollman [i], Frank Trollman [j], Carmen Carmona-Torres [a,k]

[a] Dept. Agrifood System Economics. Institute of Agricultural and Fisheries Research and Training (IFAPA). Centre 'Camino de Purchil', s/n. 18004 Granada, Spain
[b] Laboratory of Rural Economy. National Institute of Agronomic Research of Tunisia (INRAT). El Menzah 1, 1004-1001, Tunis, Tunisia
[c] Sustainable AgriFoodtech Innovation & Research (SAFIR). Arras, France
[d] Faculty of Agricultural Engineering. University of Aleppo. Aleppo, Syria
[e] Division of Engineering Logistics. Faculty of Engineering. Lund University. Lund, Sweden
[f] Sustainable Manufacturing Systems Centre. Cranfield University. Cranfield, United Kingdom
[g] Dept. Chemical Engineering. Faculty of Sciences. University of Granada. Avda. Fuente Nueva, s/n. 18071 Granada, Spain
[h] Dept. International Affairs. College of Arts and Sciences. Qatar University. Doha, Qatar
[i] Management. Centre for Sustainable Organisations. School of Business. University of Leicester. Brookfield, 266 London Road. Leicester LE2 1RQ, United Kingdom
[j] Dept. Trauma and Orthopaedics. University Hospitals of Derby and Burton. DE22 3NE Derby, United Kingdom
[k] Institute of Regional Development. University of Granada. Rector López Argüeta, s/n. 18071 Granada, Spain

ARTICLE INFO

Keywords:
Olea europaea
Olive
Digital transformation
Agri-food technology
Precision agriculture
Smart farming

ABSTRACT

Vital to the economy, culture and landscape of many regions around the world, the olive sector faces significant challenges, including rising production costs, labour shortages, climate change impacts, water scarcity, quality control issues and market demands for transparency and authenticity. Digital and other Industry 4.0 technologies offer transformative potential to address these pressures. This article provides a comprehensive review of recent applications and future prospects of technologies such as the Internet of Things, Artificial Intelligence, Machine Learning, Robotics and Automation, Big Data Analytics, Advanced Sensing, Remote Sensing, Nanotechnology and Blockchain across the olive value chain, from cultivation to supply chain management. Using a literature review methodology to identify key application areas, it synthesises evidence on how these innovations increase resource efficiency, optimise farm management, automate labour-intensive tasks, improve pest and disease control, ensure product quality and authenticity, facilitate traceability and add value through by-product valorisation. Key benefits include improved yields, reduced environmental impact, enhanced quality control, fraud deterrence and increased consumer confidence. Future prospects include deeper integration of technologies, more sophisticated AI-driven decision support, advanced robotics, widespread adoption of rapid sensing techniques, development of circular economy models and nanotechnology applications, while recognising the need for safety assessments. Overcoming barriers related to cost, digital literacy, data interoperability and equitable access, especially for smallholder farmers, is critical. This review highlights the strategic importance of embracing digital transformation to strengthen the resilience, sustainability and competitiveness of the global olive industry.

1. Introduction

The olive tree (Olea europaea L.) is one of the oldest cultivated plants, with a history spanning more than 6000 years [1]. Olive cultivation and olive oil production are integral to the economy, agricultural landscape and cultural heritage of many countries, particularly in the Mediterranean region where the tree originated [2]. Today, olive cultivation has expanded to other regions with similar climates around the world (Fig. 1), reflecting its global importance [3,4].

The olive sector is a cornerstone of the global agrifood industry. It covers over 10 million hectares and supports the livelihoods of millions

* Corresponding author at: Division of Engineering Logistics, Faculty of Engineering, Lund University, Lund, Sweden.
E-mail address: sandeep.jagtap@tlog.lth.se (S. Jagtap).

https://doi.org/10.1016/j.atech.2025.101376
Received 22 April 2025; Received in revised form 14 August 2025; Accepted 24 August 2025
Available online 25 August 2025

List of acronyms and abbreviations

AI	Artificial Intelligence
ANNs	Artificial Neural Networks
AS	Advanced Sensing
BDA	Big Data Analytics
CNNs	Convolutional Neural Networks
CPS	Cyber-Physical System
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
ddPCR	Droplet Digital Polymerase Chain Reaction
DL	Deep Learning
DSC	Differential Scanning Calorimetry
EEM	Excitation-Emission Matrix
EVOO	Extra Virgin Olive Oil
FTIR	Fourier Transform Infrared
GCMS–	Gas Chromatography/Mass Spectrometry
GIS	Geographic Information Systems
GPS	Global Positioning System
HSI	Hyperspectral Imaging
IMS	Ion Mobility Spectrometry
IOC	International Olive Council
IoT	Internet of Things
K-NN	k-Nearest Neighbours
LIBS	Laser-Induced Breakdown Spectroscopy
MIR	Mid-Infrared
ML	Machine Learning
MLP	Multilayer Perceptron
MPE	Mean Prediction Error
MUFA	Monounsaturated Fatty Acids
NFC	Near Field Communication
NIR	Near-Infrared
NMR	Nuclear Magnetic Resonance
OMWW	Olive Mill Wastewater
OOSC	Olive Oil Supply Chain
PA	Precision Agriculture
PARAFAC	Parallel Factor Analysis
PDO	Protected Designation of Origin
PGI	Protected Geographical Indication
PHAs	Polyhydroxyalkanoates
PLS-DA	Partial Least Squares Discriminant Analysis
QR	Quick Response
RA	Robotics and Automation
RF	Random Forest
RFID	Radio Frequency Identification
RS	Remote Sensing
SF	Smart Farming
UAS	Unmanned Aerial Systems
UAVs	Unmanned Aerial Vehicles
UGVs	Unmanned Ground Vehicles
UV–Vis	Ultraviolet-Visible
VOO	Virgin Olive Oil
YOLO	You Only Look Once

of people, particularly in rural areas [5]. Not only does olive growing drive economic growth, it also significantly supports rural employment, sustains livelihoods, promotes community resilience, and mitigates rural depopulation by strengthening social and territorial cohesion [6,7]. In particular, extra virgin olive oil (EVOO), which is valued for its sensory qualities and health benefits, is a significant economic contributor and a key component of the Mediterranean diet [8–10].

Despite its global importance, the olive sector is facing a number of urgent challenges. Producers are under economic pressure due to rising production costs, labour shortages during the harvest season, and market price volatility [11,12]. The high value of EVOO also makes it a prime target for fraud and adulteration, which erodes consumer trust

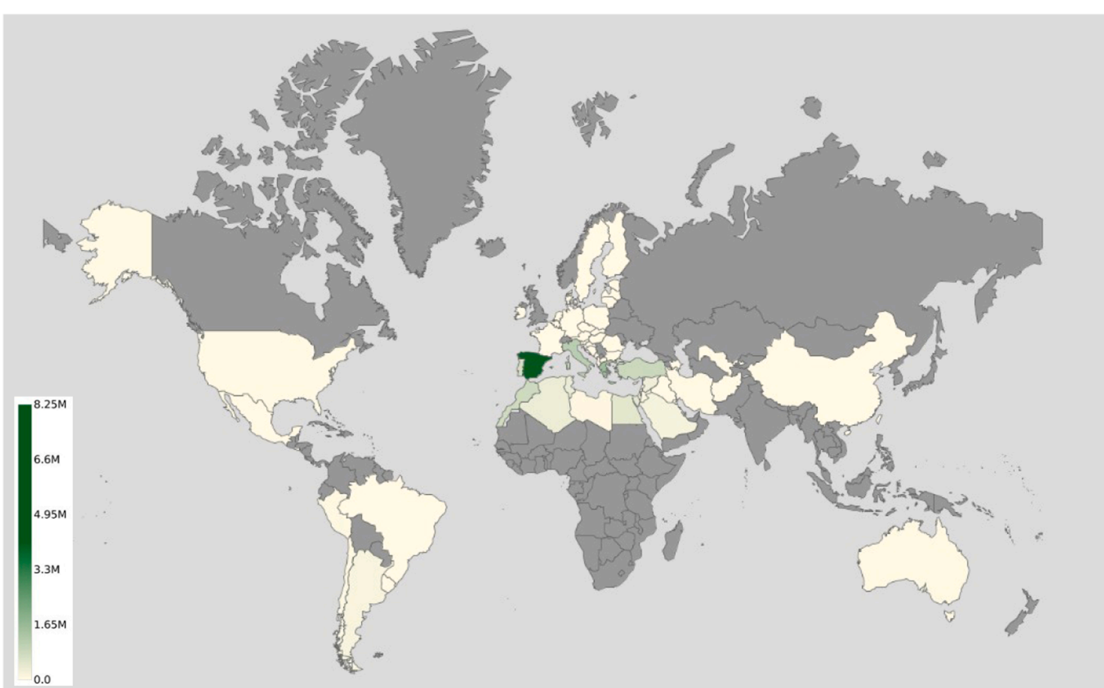

Fig. 1. Distribution of world olive production (tonnes per year).
Source: https://www.atlasbig.com/en-gb/countries-by-olive-production (based on FAO data).

[13]. The sector is often structurally fragmented and dominated by small family farms and cooperatives. This can lead to inefficiencies in production and throughout the entire Olive Oil Supply Chain (OOSC) [11, 14]. In addition, traditional practices still dominate olive growing [15, 16]. This leads to low productivity and abandonment in some traditional and marginal areas [17].

In addition, climate change poses a multifaceted environmental threat. It increases water scarcity, causes crop stress and alters the patterns of pests and diseases such as *Xylella fastidiosa* [18–22]. Furthermore, the intensive use of inputs such as fertilisers and pesticides affects costs and exacerbates environmental concerns [16,23]. Moreover, the olive oil industry produces large quantities of olive mill wastewater (OMWW) and solid residues that can be toxic to the environment if not treated properly [24].

In response to these pressures, the agriculture and agrifood sector isundergoing a transformative phase in the context of Industry 4.0, characterised by the integration of digital and other advanced technologies into agricultural and industrial practices [25–27]. Technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML), Robotics and Automation (RA), Big Data Analytics (BDA), Advanced Sensing (AS), Remote Sensing (RS) are enabling a shift towards more precise, efficient and sustainable agriculture and food industry [28,29]. Digital technologies are at the heart of this 4.0 revolution, but they are complemented by other advanced technologies such as nanotechnology and genomics. For the olive sector, digital transformation has emerged as a powerful catalyst with the potential to revolutionise growing and processing practices, improving the efficiency, sustainability and competitiveness [6,14,30].

In this respect, previous studies have focused on specific technologies or singular aspects of olive growing and processing. For example, Marques, Padua, Sousa and Fernandes-Silva [31] reviewed the application of RS imagery in olive cultivation, while Perez-Ruiz, Gonzalez-de--Santos, Ribeiro, Fernandez-Quintanilla, Peruzzi, Vieri, Tomic and Agueera [32] explored RA in olive cultivation, mainly in the context of general crop protection. Research in this area tends to focus on specific technological areas, such as precision agriculture [33–36], AI and ML [37], AS and monitoring techniques [31,38,39], digital traceability using blockchain systems [40] and sustainable waste management practices [41,42]. However, a holistic overview of the synergistic potential of multiple Industry 4.0 technologies across the entire olive value chain is lacking.

In this context, the aim of this article is to address this gap. Through a comprehensive analysis, it explores the integration of digital technologies in olive farming and the wider industry. It highlights the role of these technologies in addressing challenges, optimising productivity, and promoting sustainable practices. Examining current research, technological advances and practical applications, it identifies opportunities, barriers and future pathways for innovation in olive growing, processing and supply chain management. By doing so, it provides stakeholders with actionable insights and a strategic roadmap for embracing digital transformation, thereby improving the productivity, sustainability and competitiveness of the olive sector.

2. Methodology

A comprehensive literature review was conducted (Fig. 2) to identify recent studies and applications in the olive sector of a wide range of recognised digital technologies in the agri-food sector [26]. The Web of Science and Scopus databases were searched using specific queries for olive and digital technologies. 2860 records were identified in November 2024.

After an initial analysis of the literature and current research trends

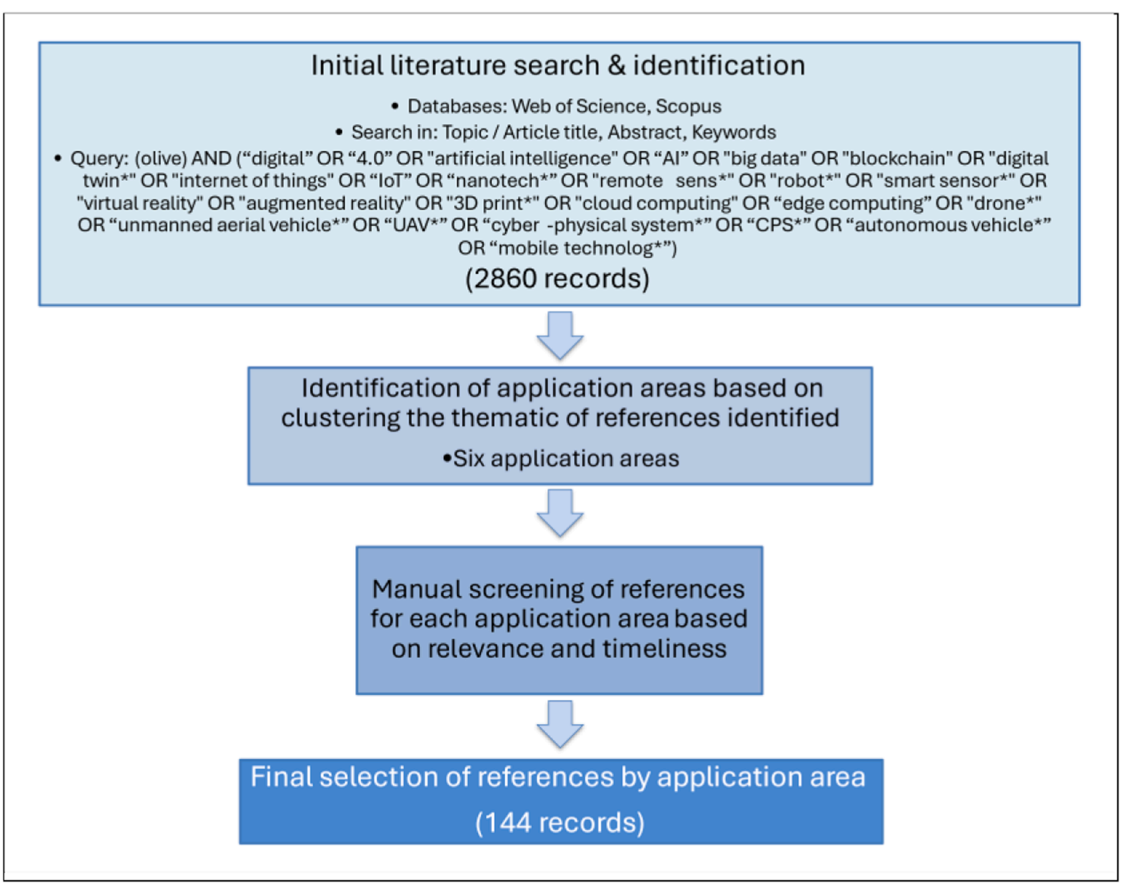

Fig. 2. Literature review process.

in the olive sector, six main application areas were identified where digital technologies have a significant impact or potential: Precision agriculture and smart farming in olive cultivation; AI and ML in olive agriculture and industry; robotics and automation in olive harvesting and processing; spectroscopic techniques, hyperspectral imaging and biosensors for olive oil quality control; nanotechnology applications in olive oil preservation and enhancement; and supply chain management and traceability. These areas were selected based on their relevance to the most pressing challenges facing the olive industry, their integration of cutting-edge technologies and their comprehensive coverage of the entire olive value chain, from cultivation to supply chain management. The publications were then manually screened for their focus and timeliness on the application of digital technologies in the olive sector and classified into the six application areas. The final pool of references consisted of 144 records, which form the basis of this article.

3. Recent applications of digital/4.0 technologies in the olive sector

This section looks at recent applications of modern digital and other 4.0 technologies in the olive sector. From precision agriculture and AI optimising farm management and quality control, to robotics automating harvesting and processing, these innovations are improving efficiency and yields. In addition, sophisticated sensing techniques and nanotechnology are improving oil quality analysis and preservation, while blockchain and IoT are ensuring greater transparency and traceability throughout the supply chain. This is discussed in detail in the following sections and summarised in Table 1.

3.1. Precision agriculture and smart farming in olive cultivation

There are a number of terms used to refer to agricultural practices that use digitalisation technologies. Precision Agriculture (PA) and Smart Farming (SF) are terms used to describe the use of innovative technologies to collect large amounts of data and use it to make informed decisions. This modern form of agricultural production has the advantage of making more efficient use of agricultural inputs (mainly fertilisers, pesticides and water), reducing losses and increasing yields. It can also facilitate more accurate planning of different agricultural activities, as demand for food products can be more accurately predicted. These benefits are achieved by using technologies to monitor variables such as soil moisture, nutrient levels and pest presence with high spatial and temporal resolution. This enables precise, data-driven interventions to be carried out, such as applying water or fertiliser only when and where needed. This reduces input costs, minimises environmental impact and optimises crop health and yield.

Indeed, a considerable amount of research has been devoted to investigating the potential of PA and SF in the olive oil sector. For example, it has been shown that PA facilitates the prediction of the nitrogen content in olive tree leaves using hyperspectral data [43], which is significant given that nitrogen is the main limiting factor for olive trees after water. Nappa, Quartulli, Azpiroz, Marchi, Guidotti, Staiano and Siciliano [44] tested their PA approach based on neural networks for predicting olive phenology, providing important data on the life cycle of olive trees. Similarly, SF approaches have demonstrated benefits in the olive sector, including the improvement of irrigation systems through the use of IoT [45] and unmanned aerial vehicles (UAVs) [46], and disease control based on deep learning [47] and linear mixed effects models [48]. SF has also been shown to reduce the environmental impact of olive growing and harvesting [49].

In recent years, there has been a significant increase in the use of sensors in agriculture in general and in the olive oil sector in particular. Digital sensors have been shown to facilitate the acquisition of more accurate data compared to conventional systems, offering significant advantages in the assessment of olive tree health and olive quality. For example, a nitrogen-doped nanocrystalline electrochemical graphite

Table 1
Summary of recent applications of digital/4.0 technologies in the olive sector.

Application area	Key technologies	Applications	Key benefits/ outcomes
Precision agriculture and smart farming	Precision Agriculture (PA); Smart Farming (SF); Sensors (Hyperspectral, Electrochemical); IoT; UAVs (Drones); Remote Sensing (Satellites); GIS; Big Data Analytics	Prediction of leaf nitrogen, olive phenology; Improvement of irrigation systems; Disease control; Detection of oleuropein (quality control); Real-time data transmission & automation (irrigation, fertilisation, pest control); Ripening, health, soil, water stress monitoring; Site suitability assessment; Autonomous spraying; Managing & analysing large data sets (irrigation efficiency, agroclimatic influence, genetics, milling/harvest optimisation)	More efficient use of inputs (water, fertiliser, pesticides); reduced losses, increased yields; accurate planning, reduced costs; environmental benefits; improved data accuracy & quality control; improved supply chain performance; effective large scale monitoring; optimal resource management
Artificial intelligence and machine learning	Artificial Intelligence (AI); Machine Learning (ML); Predictive Modelling; Deep Learning (DL); Image Recognition; ANNs; YOLO	Yield estimation/ forecasting; Early disease detection & diagnosis; Olive ripeness assessment (counting, staging); Optimisation of processing parameters & oil blending; Quality assessment & fraud detection (authenticity, adulteration)	Data-driven decision making; accurate forecasting & planning; optimised production & resource management; reduced chemical use; Improved oil quality & consistency; Improved fraud detection & authenticity verification
Robotics and automation	Robotics & Automation (RA); Shakers (Trunk, Canopy); UAVs; Autonomous Systems; Sensors (Laser, Infrared); Machine Vision; AI (YOLO, CNNs); Remote sensing	Automated harvesting & transport; autonomous guidance & navigation in groves; real-time defect detection & quality assessment (size, ripeness, bruising); fermentation monitoring; automated tree counting & yield estimation; robotic pest & disease monitoring (traps, xylella detection); automated sorting & logistics	Increased efficiency & productivity; Reduced labour requirements & costs; Improved harvesting efficiency; Improved quality control & accuracy; Accurate yield estimates; Improved pest & disease management; Sustainability benefits
Spectroscopy, HSI and biosensors	Spectroscopy (NIR, MIR/FTIR, Fluorescence, Raman, NMR, LIBS, UV–Vis); Hyperspectral	Chemical Composition Analysis (Fatty Acids, Polyphenols); Quality & Purity	Detailed chemical insights; Rapid, non-destructive analysis High accuracy in

(continued on next page)

Table 1 (*continued*)

Application area	Key technologies	Applications	Key benefits/ outcomes
	Imaging (HSI); Computer Vision; Biosensors (Electrochemical, Enzymatic, DNA-based); E-Noses; Chemometrics; ML	Assessment; Adulteration Detection & Authenticity Verification; Grade & Geographical Differentiation; Shelf Life & Oxidation Monitoring; Automated Monitoring (HSI); Physical Defect Detection (Computer Vision); Real-Time Detection of Bioactive Compounds (Oleuropein); Volatile Profile Analysis (e-Nose)	quality control & authentication; On-site & industrial applicability; Effective fraud detection; High sensitivity for key compounds; Reduced reliance on traditional laboratory methods; Potential for large-scale screening
Nanotechnology	Nanoparticles (Chitosan, Lipid Carriers, Silver); Nanoemulsions; Nanophytosomes; Nanocapsules; Cellulose nanocrystals; Nano-fertilisers	Enhancing the bioavailability of nutraceuticals (polyphenols); Targeted drug delivery (health applications: (health applications: psoriasis, cholesterol, cancer); antimicrobials (plant & human health); improving stability/taste of compounds; remediation of toxic elements; cosmetics (anti-aging, hair care); plant protection & disease resistance; improving plant yield & growth (nano-fertilisers); decontamination of micropropagation; improving animal growth (aquaculture); Food packaging (safety concerns identified)	Value added from olive products/waste; Improved efficacy of beneficial compounds; Novel health & cosmetic applications; Sustainable alternatives to agrochemicals Improved plant health & productivity; Potential for improved food preservation; Requires careful safety assessment
Supply chain management and traceability	Blockchain; IoT; Sensors; Mobile interfaces (apps, web); Smart contracts; RFID/ NFC; QR codes; GPS; DNA-based technology; Analytical techniques (NMR, DSC)	Create secure, immutable records of OOSC activities; Real-time monitoring (cultivation, transport, storage); Automated verification (quality, conditions) via smart contracts; Batch tracking & identification (RFID/NFC/QR); Verification of origin (geographic, varietal) via GPS, DNA; Provide consumers with access to verifiable product history	Increased transparency, security, efficiency; Improved traceability from grove to consumer; Improved food safety & quality assurance; Increased deterrence of fraud & adulteration; Increased consumer trust & brand value; Support for regulatory compliance & certifications; Reduced information asymmetry

sensor has been used to detect oleuropein, a natural compound found mainly in olive leaves, olives and olive oil [50]. The detection of oleuropein and other compounds is crucial in the olive oil quality control process, which was previously based on chemical analysis and organoleptic evaluation. The use of sensors for olive oil quality control has also been advocated by other authors [51,52].

The integration of sensors into IoT systems (networks of interconnected physical devices that collect and exchange data) facilitates the interconnection of these systems, allowing the recording and transmission of data in real time. This development has significant implications for the automation and precise management of irrigation, fertilisation and pest control in olive cultivation [53]. IoT has been shown to offer significant benefits not only in olive farms, but also in the olive oil industrial sector, for example by controlling olive pitting, slicing and stuffing machines with IoT systems [54]. Overall, the implementation of IoT in the olive oil sector has the potential to improve the performance of the entire OOSC by integrating it into supply chain activities such as demand planning, manufacturing, transportation, customer service, warehousing and inventory management [55]. The benefits of IoT can be enhanced by integrating it with other digital technologies, such as blockchain, to increase transparency and reduce fraud risks in the olive oil market, which would support consumer confidence and promote regulatory compliance [56].

Sensors can also be integrated into UAVs, such as drones. This will allow effective monitoring of the ripening stage and health of olive trees and their soils with higher spectral and energy efficiency [46,48,57,58]. This is of particular interest in the context of climate change, which is already significantly affecting the water status of olive orchards [33], as olive trees are mostly grown in drought-prone regions. The use of RS techniques, using satellite-based multispectral imaging (which captures image data at specific frequencies across the electromagnetic spectrum), holds great promise for extending the scope of field monitoring to a much larger scale, so that entire olive orchards can be monitored continuously [59–61]. The data collected in this way can be managed and analysed using Geographic Information Systems (GIS), which are specialised systems for capturing, storing, analysing, and displaying geographically referenced data. This approach facilitates the assessment of potential olive grove sites, allowing informed decisions to be made about their suitability [62,63]. For example, GIS systems, RS and other technologies can be used together to assess water stress [64], which facilitates the implementation of optimal irrigation strategies [65]. In addition to RS, UAVs have the potential to act as autonomous sprayers in olive orchards, with high phytosanitary efficiency, reduced water consumption, reduced soil compaction [66], increased spraying precision and reduced air drift, thus reducing environmental exposure to pesticides and fertilisers [67].

The significant amount of data that these sensors can collect may require the implementation of BDA (the process of examining large and varied data sets to uncover patterns and insights) to facilitate the effective storage, analysis and sharing of information. However, there is a paucity of research focusing on the use of BDA in the olive oil sector. Examples of research include an assessment of irrigation efficiency for optimal olive production [68] and a study of daily agroclimatic data and its influence on the fatty acid profile of olive oil [69]. Furthermore, recent projects have investigated the potential applications of BDA in the olive oil and table olive industries. For example, the EU H2020 project GEN4OLIVE (www.gen4olive.eu) uses BDA and AI to analyse the genetic information of olive trees for breeding and conservation purposes. The Spanish operational group GO STOW 4.0 (www.encomaquinaria.com/stow-4–0/) aims to transform the table olive industry into an Industry 4.0 model by optimising resource use and improving product quality through the IoT and BDA. The Spanish SMART-O-LIVE R&D project (https://datalab.upo.es/project/smart-olive/) aims to modernise the entire olive oil supply chain (from the field to the mill and the packaging line) by integrating BDA, AI, and other digital technologies. The EU H2020 project DataBio (www.databio.eu) supports the development of a sustainable bioeconomy by applying big data to agriculture, including olive production. Some solutions have reached commercial maturity. These include AI- and BDA-based predictive and optimisation tools developed by the Citoliva technology centre (www.citoliva.es) to improve harvest timing and milling efficiency, and by the engineering firm Pastrana Ingeniería (www.pastranaingenieria.com), which uses BDA and ML to enhance olive harvesting and milling processes.

3.2. Artificial intelligence and machine learning in olive agriculture and industry

The application of AI, which involves the simulation of human intelligence processes by machines, and ML, a subfield of AI, in the olive sector is driving a paradigm shift towards data-driven decision making, enabling accurate forecasting, optimised production and improved resource management. AI and ML provide advanced analytical tools to process vast amounts of agricultural data, helping farmers and industry stakeholders to make informed, data-driven decisions in many areas, such as yield estimation, disease detection, quality control, etc.

Yield estimation is a critical aspect of olive growing, influencing supply chain management, resource allocation and market planning. Traditional methods rely on manual assessments and historical averages, often failing to capture dynamic environmental variables. AI-based predictive modelling improves accuracy by using ML algorithms that process multiple datasets. For example, Cubillas, Ramos, Jurado and Feito [70] developed a predictive yield forecasting model for olive orchards in Andalusia, Spain. Using eight years of historical yield data and more than twenty meteorological parameters automatically retrieved from public web services, the model enables early predictions, made at the beginning of the year, with a margin of error of less than 20 %. The novelty of this approach lies in its timing; unlike traditional models that rely on post-pollination data from May or June, this early forecast provides crucial information before significant financial commitments are made for the season. Consequently, this allows farmers to make better-informed strategic decisions, such as adjusting the intensity and cost of tillage based on the expected yield or securing more favourable prices by pre-negotiating sales contracts. This demonstrates the practical impact of AI-driven predictive analytics in optimising farm management and economic planning.

Otherwise, olive production faces significant challenges from pests, weeds and diseases (e.g. olive scab and olive leaf spot) that negatively affect yield and olive oil quality. Accordingly, early disease detection is essential to prevent significant yield losses and minimise chemical interventions [71]. Traditionally, growers rely on visual inspection or laboratory tests. However, these methods can be time-consuming, prone to human error, often detect diseases only after significant damage has occurred, and are difficult to implement in large-scale intensive agriculture [72]. Accordingly, AI-driven image recognition systems and predictive models facilitate proactive management of olive diseases. For example, with advances in AI and deep learning (DL), automated disease detection systems such as optimised artificial neural networks (ANNs) offer a faster, more accurate and scalable alternative, enabling early diagnosis and improved crop management, as observed in Saudi Arabia [73] and Jordan [74].

AI can also be used to assess and measure the ripeness of olives, providing valuable insights for optimising harvest timing, oil quality and extraction techniques. Identifying the ripening stage of olives adds value for producers and consumers by optimising harvest timing, oil quality assessment and extraction techniques. In this regard, Mendes, Lima, Costa, Rodrigues, Leitão and Pereira [75] present an AI-based method using deep learning algorithms You Only Look Once (YOLO) (YOLOv7 and YOLOv8) to identify and count olives entering the mill, while determining their maturation stage. The results show the feasibility of implementing this system in real-world environments, with YOLOv8 achieving a 79 % mAP across five ripening stages at 16 FPS, while YOLOv7 increased the processing speed to 36.5 FPS with a 66 % mAP.

Otherwise, the production of high quality olive oil depends on several processing parameters, such as harvesting time, malaxation conditions, extraction methods and storage protocols [76]. AI technologies can play a crucial role in optimising these factors. For example, AI models can analyse chemical composition data to formulate optimal olive oil blends, ensuring consistency in taste, flavour and quality. Aroca-Santos, Cancilla, Pariente and Torrecilla [77] developed a simple AI-based method using visible spectroscopy and artificial neural networks (ANNs) to both identify the EVOO varietal and quantify the level of adulteration in blends containing refined olive oil. A multilayer perceptron (MLP) model achieved 100 % varietal identification accuracy and a mean prediction error (MPE) of 2.14 % for quantifying blends containing 0–20 % refined oil. This low-cost, user-friendly approach provides a reliable online screening tool for olive oil characterisation.

AI also plays a crucial role in assessing and ensuring the quality of olive oil and in detecting fraud. Edible oils are among the most adulterated food products in the world, and olive oil is no exception. It is estimated that 75–80 % of the EVOO sold in the United States is adulterated, while in Italy, EVOO fraud is a multi-billion euro industry, valued at around 16 billion euros [78]. Therefore, several AI-driven innovations can improve fraud detection and ensure greater accuracy, efficiency and reliability in identifying adulterated olive oils. For example, Brazil, the world's second largest importer of olive oil, has recently started small-scale production in two regions. Brilhante, Bizzo, Caratti, Squara and Cordero [79] used AI-driven volatilome analysis to ensure authenticity and detect fraud, identifying 51 key volatile compounds that serve as a chemical fingerprint. The results of this complex chemical analysis were then represented using computer vision-based visualisation techniques, allowing the AI to successfully differentiate between the two olive cultivars under study (Arbequina and Koroneiki) from Brazil's main producing regions, marking the first successful detection of mislabelled products.

3.3. Robotics and automation in olive harvesting and processing

RA, which involves the use of machines to perform tasks automatically, play an important role when it comes to digitalisation, and they are a key component of the Industry 4.0/5.0 industrial revolution in the agri-food sector. There are several reasons for integrating RA in olive harvesting and processing. First, incorporating RA into agri-food supply chains increases efficiency and productivity, and this is true for the olive sector. For example, automated harvesting systems such as trunk shakers [80], which remain the most widespread technology [81], canopy shakers [82] and UAVs [83,84] support navigation and optimise the olive harvesting process, reducing the time and labour required. Autonomous service systems also enhance manual harvesting by transporting olives and tracking yields, which in turn improves efficiency by up to 45 % [85]. Penizzotto, Slawinski and Mut [86] presented a laser radar-based autonomous guidance system for mobile robots in olive groves, using an extended Kalman filter for state estimation and odometry-based rotation. Colmenero-Martinez, Blanco-Roldán, Bayano-Tejero, Castillo-Ruiz, Sola-Guirado and Gil-Ribes [80] developed an automatic trunk detection system using infrared sensors for olive harvesting with trunk shakers, reducing operator dependency and improving efficiency by 27.3 %, achieving a 91–92.9 % success rate in trunk grabbing. In terms of path tracking and navigation, Auat Cheein, Scaglia, Torres-Torriti, Guivant, Prado, Arnò, Escolà and Rosell-Polo [85] developed an algebraic path tracking controller for an automated service unit to support manual olive harvesting, improving efficiency by 42–45 %, while Sola-Guirado, Ceular-Ortiz and Gil-Ribes [82] developed an automated canopy contact system for lateral canopy shakers in olive harvesting, using distance measurement and hydraulic pressure sensing to optimise shaker positioning. Compared to manual control, automation increased removal efficiency by 5.9 %.

There is a growing problem of labour shortages in olive harvesting and processing, a key driver for mechanisation across the sector [81,87]. Many producing regions, such as Chile and Argentina, face a decline in available agricultural labour, making robotic solutions that reduce dependence on manual labour and lower operational costs increasingly vital [88]. These authors reviewed the state of the art in agricultural robotics and proposed human-robot collaboration strategies for tasks such as harvesting, balancing automation and labour integration. On the other hand, Fountas, Mylonas, Malounas, Rodias, Hellmann Santos and Pekkeriet [89] presented a systematic review of agricultural robotics for field operations, highlighting advances in harvesting and weeding, while identifying gaps in disease detection and seeding automation. They emphasised the need for faster algorithms, improved communication and AS for future optimisation.

The automation of harvesting and quality control relies heavily on machine vision and AI models to guide robotic actions. For instance, models such as YOLO [83,90] and Convolutional Neural Networks (CNNs) [91] can detect defects in olives in real time, which can ensure good quality of olives and olive oil and improved accuracy. Sola-Guirado, Bayano-Tejero, Aragón-Rodríguez, Bernardi, Benalia and Castro-García [92] developed an affordable, field-based smart system using computer vision to automatically assess the quality of green olives, including size, ripeness and bruising, providing farmers with instant assessments to aid decision making. Some researchers presented a machine vision-based method using RGB image analysis and k-nearest neighbours (K-NN) classification to determine olive ripeness in real time [93]. Others presented an automated monitoring device for tracking key fermentation parameters in table olive brine to ensure product quality and stability. The low-cost, sensor-equipped system demonstrated high reliability, allowing continuous monitoring to improve sustainability and process control in olive fermentation [94]. Cano Marchal, Satorres Martínez, Gómez Ortega and Gámez García [95] presented an automated defect detection system using infrared imaging and image processing techniques to identify damaged olives in oil mills. Some researchers developed a fast and automated olive quality assessment system using RGB imaging and YOLO-based CNNs to classify olives by defects and ripeness [91].

RA has also helped to optimise yield estimation and resource management in the olive sector. For example, automated tree counting and fruit detection using RS and UAVs provide accurate yield estimates, supporting better planning and inventory management [96]. Multispectral imagery and vegetation indices also help to monitor crop health and optimise irrigation and fertilisation [97]. Aljaafreh, Elzagzoug, Abukhait, Soliman, Alja'Afreh, Sivanathan and Hughes [90] developed a real-time olive fruit detection system for harvesting robots using YOLOv5 deep learning models to improve yield estimation. Waleed, Um, Khan and Ahmad [96] presented an automated RS method for olive tree detection and counting using image processing techniques on red band images. The system achieved high accuracy with an estimation error of only 1.27 %. Similarly, Aquino, Ponce and Andújar [98] presented a CNN-based method for automatic olive fruit identification in intensive orchards using night-time field images and the OLIVEnet dataset. The best performing CNN achieved 83.13 % accuracy for olive detection and 99.12 % for non-olive classification, marking a significant step towards automated yield estimation in olive production. Karabatis, Lin, Sanket, Lagoudakis and Aloimonos [99] presented a novel approach to olive detection using a mixture of synthetic and real data, using a photorealistic 3D model to generate automatically labelled images, significantly improving detection accuracy while reducing the need for manual labelling.

RA has also contributed to improved pest and disease monitoring in olive harvesting and processing. Pest control strategies such as robotic monitoring of insect traps can minimise damage to olive crops, particularly for *Bactrocera oleae* [83,84]. Similarly, the integration of RS, AI and UAVs can help in the early detection of *Xylella fastidiosa* and prevent the spread of the disease [100]. Berger, Teixeira, Cantieri, Lima, Pereira, Valente, Castro and Pinto [83] developed a cooperative robotic system using Unmanned Aerial Systems (UAS) and Unmanned Ground Vehicles (UGVs) for autonomous insect trap monitoring in olive groves. Using YOLO-based vision and fuzzy control algorithms, the system enables efficient navigation, inspection and UAS-UGV coordination, and demonstrates feasibility through real-world simulations. XF-ROVIM, a low-cost field robot equipped with thermal, spectral, and structural sensors for early detection of *Xylella fastidiosa* in olive groves, was developed by Rey, Aleixos, Cubero and Blasco [100]. Some researchers evaluated UAV-assisted semi-autonomous navigation for insect trap inspection in olive groves, using fiducial markers (Ar_Track_Alvar) as visual reference points. Experimental tests with a DJI Tello drone demonstrated the feasibility of computer vision-based marker tracking for efficient UAV navigation in both indoor and outdoor environments [84]. Similarly, Arvaniti, Rodias, Terpou, Afratis, Athanasiou and Zahariadis [101] reviewed smart agriculture technologies such as RS and monitoring algorithms for pest and disease management.

RA also offers significant sustainability and traceability benefits. Environmentally, automated systems improve resource management by, for example, monitoring fermentation to reduce waste [94] and enabling PA approaches that minimise agrochemical use. In terms of traceability and optimisation, technologies such as DNA-driven authentication [102] and computer vision for batch sorting [103] enhance supply chain integrity and production efficiency. Gila, Puerto, Garcia and Ortega [103] presented an automated computer vision-based system for classifying olives prior to oil production, using image histograms and Fisher's discriminant analysis to differentiate between tree-harvested and ground olives, achieving 100 % classification accuracy for improved milling efficiency. In addition, automated logistics and tracking approaches streamline post-harvest handling, processing and distribution, reducing waste and inefficiencies. In terms of supply chain traceability, Auat Cheein, Scaglia, Torres-Torriti, Guivant, Prado, Arnò, Escolà and Rosell-Polo [85] explored the role of unmanned robotic service units in PA, highlighting their potential for autonomous task execution in weed detection, agrochemical application, irrigation and terrain levelling. It emphasised the shift from manned to autonomous agricultural vehicles, enabling continuous field monitoring and data-driven decision making.

3.4. Spectroscopic techniques, hyperspectral imaging and biosensors for olive oil quality control

Spectroscopic techniques are fundamental to the analysis of the chemical composition of olive oil, providing detailed insights into quality and purity. These methods work by measuring the interaction between matter and electromagnetic radiation. Near-infrared (NIR), mid-infrared (MIR), Raman and fluorescence spectroscopy are widely used due to their ability to detect and quantify chemical markers related to the quality and authenticity of olive oil [104].

NIR spectroscopy is a non-destructive method that is effective in determining fatty acid profiles, polyphenol content and detecting adulterants. Its rapid analysis makes it ideal for industrial quality control. Studies highlight the ability of NIR to differentiate EVOO from inferior grades, thus ensuring product authenticity [105–107]. Portable and miniaturised NIR instruments coupled with advanced models accurately predict quality parameters such as acidity with high coefficients of determination (R^2) [108,109]. NIR spectroscopy is also valuable for detecting adulteration of olive olil with other seed oils, achieving high R^2 values in quantification [110]. It can detect adulteration even at low levels (2.7 %) when combined with chemometric techniques, demonstrating its usefulness for rapid fraud detection [111].

MIR spectroscopy provides comprehensive information about molecular vibrations, which is crucial for identifying specific chemical bonds and functional groups [112]. This technique is valuable for authentication by identifying unique spectral fingerprints. Fourier Transform Infrared (FTIR) spectroscopy, a type of MIR, combined with ML, specifically Random Forest (RF) algorithms, effectively differentiates EVOO from lower quality oils [113]. Characteristic spectral bands, such as carbonyl groups and fingerprinting regions, contribute to high classification accuracy, demonstrating the robustness of FTIR for olive oil authentication.

Fluorescence spectroscopy uses the natural fluorescence of compounds to assess antioxidant capacity and overall quality. Its high sensitivity allows detection of low concentrations of fluorescent compounds called fluorophores. Innovations in portable fluorescence spectroscopy instruments facilitate on-site quality assessment. Fluorescence spectroscopy is effective in monitoring the shelf life of virgin olive oil, correlating fluorescence components with oxidation parameters to predict quality deterioration [114]. Combined with ML, it quantifies oxidation effects during EVOO ageing [115]. In addition, fluorescence spectroscopy with chemometric tools accurately detects and quantifies olive oil adulteration [116]. Excitation-emission matrix (EEM) fluorescence spectroscopy enhanced with parallel factor analysis (PARAFAC) effectively quantifies adulterant levels, demonstrating its practical application in food safety [117]. Fusion of EEM fluorescence and NIR spectroscopy data further improves the accuracy of EVOO authentication, confirming the synergistic benefits of combined spectroscopic approaches [118].

Raman spectroscopy offers high sensitivity to molecular vibrations, enabling the detection of minor components and adulterants. Its versatility increases its applicability in olive oil analysis. Raman spectroscopy has been studied alongside fluorescence spectroscopy for olive oil quality classification, although fluorescence often shows superior performance [119]. However, Raman spectroscopy is effective in classifying olive oils by geographical origin, with high accuracy (94.37 %) using partial least squares discriminant analysis (PLS-DA) with spectral bands related to fatty acid vibrations [120]. Combining Raman with NIR spectroscopy improves the accuracy (over 97 %) of geographical identification of EVOO [121]. Raman and NIR spectroscopy were found to be less effective than FTIR for screening virgin olive oils, with FTIR being more relevant for lower quality oils due to its sensitivity to carbonyl and polar groups [122].

Other spectroscopic techniques, such as nuclear magnetic resonance (NMR), are used to predict nutritional parameters, assess oxidation and verify the authenticity of olive oils [123,124]. For example, high-resolution ^1H NMR with multivariate analysis detects adulteration with high sensitivity [125]. Laser-induced breakdown spectroscopy (LIBS) is gaining traction for rapid adulteration detection by analysing elemental composition in real time. LIBS and ultraviolet-visible (UV–Vis)-NIR spectroscopy show comparably high accuracy in detecting adulteration (up to 97 %), with LIBS offering faster results [126]. In addition, ML based LIBS shows exceptional classification performance, approaching 100 % accuracy in discriminating between pure and mixed EVOOs [127].

Otherwise, the rise of Industry 4.0 is driving the development of automated monitoring systems such as hyperspectral imaging (HSI) and computer vision. HSI captures detailed chemical and spatial information, while computer vision identifies defects, colour, shape, size and textura [105,112,128]. HSI with PLS-DA has shown superior classification accuracy in detecting EVOO adulteration compared to FTIR, Raman, UV–Vis spectroscopy and gas chromatography/mass spectrometry (GC–MS) [129]. Fluorescence HSI may be slightly less accurate than FTIR, but offers greater efficiency for large-scale industrial screening [130]. Computer vision applications in olive oil analysis have shown potential in estimating impurity content with high classification rates (87.66 %) using methods such as kernel principal component analysis and support vector machines [131].

Finally, biosensors and electronic sensing devices, which use biological components or synthetic mimics to detect specific chemical substances, are advancing olive oil quality assessment by providing rapid, cost-effective and portable solutions. These tools facilitate real-time detection of bioactive compounds, adulteration and authenticity verification, reducing the reliance on traditional methods [132]. Electronic noses (e-noses) are used to authenticate olive oil by analysing volatile profiles, achieving high accuracy in verifying the status of Protected Designation of Origin [133] and differentiating EVOO and Virgin Olive Oil (VOO) based on fruitiness [134]. E-noses integrated with chemometric models also classify olive oils according to perceived fruitiness [135]. Electrochemical and enzymatic biosensors detect key bioactive compounds such as polyphenols and oleuropein. Tyrosinase-based enzymatic biosensors show high sensitivity and allow accurate quantification of oleuropein in EVOOs [136]. DNA-based biosensors offer a specific approach for detecting adulteration of olive oil by other vegetable oils, effectively detecting adulteration at low levels (5–10 %) [137].

3.5. Nanotechnology for value-addition and enhancement of olive products and by-products

Nanotechnology, the manipulation of matter on an atomic and molecular scale, can be related to many parts of olive production: oil, leaves and waste. Olive oil production produces a lot of waste, rich in hydroxytyrosol and secoiridoid derivatives (phenolic compounds or polyphenols), which are associated with health benefits. Oleuropein and verbascoside, important for their antimicrobial potential, are also present, along with elenolic acid, an antimicrobial and antiviral agent resulting from the degradation of oleuropein [138].

There is considerable interest in nanotechnologies for the treatment of many types of human diseases and conditions. One of the major problems associated with the consumption of polyphenols as nutraceuticals is bioavailability. This includes low absorption and poor penetration across biological barriers such as the skin [139]. Nanoparticle encapsulation strategies for hydroxytyrosol are chitosan nanoparticles and poly-D-L-lactide-co-glycolic-co-acrylic acid nanoparticles, while oleuropein is commonly used with lipid nanostructured carriers and chitosan nanoparticles [140].

Lipid nanostructured carriers can be used for a variety of applications. Liquid lipids from natural vegetable oils that contain numerous antioxidant compounds, such as olive oil, can be used to deliver antioxidants across the gastrointestinal barrier [141]. Olive oil has been used in the preparation of lipid nanostructured carriers as an innovative natural treatment for psoriasis [142]. An olive oil-based lipid nanostructure carrier containing atorvastatin was investigated to help control high lipid levels, especially bad cholesterol, to reduce the prevalence of obesity [143]. Olive oil-based liquid nanocapsules have been developed as nanocarriers for lipophilic drug delivery targeting pancreatic cancer stem cells with enhanced antitumour efficacy [144].

There are many other olive-derived nanotechnology strategies related to human health. Silver nanoparticles synthesised from olive leaf extracts have shown potential as antimicrobial agents - inhibiting the growth of yeast, gram-positive and -negative bacteria [145]. An olive oil nanoemulsion containing curcumin was investigated as a viable approach for the treatment of bacterial infections caused by multidrug-resistant *K. pneumoniae* [146]. Ozonated olive oil, which has the disadvantages of limited water solubility and poor transdermal penetration, has been used with nanocarrier host molecules to improve these shortcomings for use as a melanoma treatment [147]. Olive leaf extract, mainly containing oleuropein and rutin, has been loaded into nanophytosomes to evaluate its anti-colon cancer activity as a passive tumour-targeted therapy due to its improved stability and efficacy

[148]. Hydroxytyrosol-loaded nanocapsules have been investigated for use in pharmaceutical and nutraceutical products to combat low water solubility, bitter taste and instability to oxidation in the atmosphere for the treatment of several diseases based on oxidative-inflammatory environments [149]. Nanotechnology has also been proposed as a remediation method for toxic trace elements in food [150]. Specifically, toxic trace elements may be introduced into olive oil during the manufacturing process and may also be absorbed into the plant from the soil.

The cosmetics industry is also exploring nanoformulations for nanocosmeceuticals. Conventional anti-aging products for the skin have a large particle size, making them less effective. Nanotechnological approaches for topical anti-aging products show promise for olive oil as a skin conditioner and antioxidant, with a number of commercial products already on the market [151]. Nanoemulsions also have potential applications in hair products. A study of the hair treatment efficacy of coconut, olive and Abyssinian oils found no significant difference between them in terms of combing efficacy [152].

Similarly, nanotechnologies can be used to benefit plants. The copper salts currently used to prevent bacterial plant diseases are dangerous to ecosystems and have favoured the selection of resistant strains. Nanotechnology could provide an alternative to traditional agrochemicals. Cellulose nanocrystals obtained from olive tree pruning waste show promise as a sustainable plant protection strategy against, for example, olive knot disease (*Pseudomonas savastanoi pv. savastanoi*), while reducing the use of traditional agrochemicals [153]. A novel nanostructured formulation was proposed and shown to be fully biocompatible and able to increase transcript levels of the major systemic acquired resistance-responsive genes in olive plants [154]. Olive leaf spot, a widespread disease in all olive growing areas that can cause severe yield losses, may be treatable with nanotechnology [155]. Foliar application of nano-chelated nitrogen fertiliser to olive trees improved yield and mineral composition, especially in the first year [156]. Replacing half the recommended dose of mineral fertiliser with sprayed nanofertiliser on olive seedlings was found to positively promote vegetative growth parameters without deficiency symptoms [157]. Olive micropropagation was also studied to determine the efficacy of nanoparticles as microbial decontamination agents, finding effective in vitro disinfection and good effects on the development and multiplication rate of olive shoots [158]. Other studies of nanoparticles on in vitro olive shoot growth dynamics support these findings (e.g., [159,160].

Animals can also benefit from nanotechnologies based on olive production, but there is comparatively little research compared to human and plant studies. A nanoemulsion of curcumin-loaded olive oil on shrimp was found to be a promising strategy for improving growth performance, feed utilisation and size of shrimp - improving economic performance while promoting sustainable practices [161].

Another key application of nanotechnology is in food packaging materials. However, this application raises important safety questions. For instance, studies using olive oil as a food simulant have evaluated the potential for silver nanoparticles to migrate from packaging into food [162]. This is a significant concern, as research shows that nanomaterials can potentially damage human cells by altering mitochondrial function [163] or inducing immune modulation [164]. The challenge is compounded by a lack of specific regulations for nanomaterials in the food industry [165]. Therefore, while nanotechnology offers many potential benefits, a consensus in the literature highlights that the challenges of rigorous safety assessment must be addressed to ensure consumer protection [166].

3.6. Supply chain management and traceability

The OOSC, which involves multiple stages from cultivation to consumption, often lacks transparent information sharing and documented proof of handling, leading to opacity and significant risks related to product quality, spoilage and authenticity, including fraud [167,168]. This complexity makes traceability a critical yet challenging requirement, essential for ensuring food safety, verifying origin claims such as Protected Designation of Origin (PDO), meeting regulatory requirements and, crucially, building consumer confidence, which is often undermined by fraud and adulteration scandals prevalent in the high-value EVOO market [169–171].

Digital transformation, led by technologies such as blockchain, IoT and mobile interfaces, offers a promising paradigm shift that enables improved security, transparency, and efficiency across the OOSC [172,173]. In particular, blockchain technology serves as a foundational element, acting as a decentralised, distributed, and immutable digital ledger where transactions and critical data points are securely and transparently recorded across a network of participants [40,102,174]. This inherent resistance to tampering provides a single, verifiable source of truth that reduces information asymmetry and fosters trust among stakeholders, from farmers to consumers [56,168,169].

Research and pilot projects have explored different blockchain platforms in the olive sector, including permissioned systems such as Hyperledger Fabric [175] and public ledgers such as Ethereum [176], sometimes in multi-chain architectures that include private chains such as Quorum to balance confidentiality with public accessibility [177]. The integration of smart contracts further enhances this framework by automating verification processes based on pre-defined rules, such as checking temperature thresholds during transport or validating quality parameters of olive oil, thus reducing manual errors and potential disputes [56,168].

The integration of IoT devices and sensors serves as the primary mechanism for capturing and recording reliable, real-time operational data on a secure blockchain ledger, enabling the enhanced traceability demonstrated in the systems proposed by Arena, Bianchini, Perazzo, Vallati and Dini [175], Vitaskos, Demestichas, Karetsos and Costopoulou [56], and Tang, Tchao, Agbemenu, Keelson, Klogo and Kponyo [178]. These technologies bridge the physical reality of the olive oil journey with its digital representation. Specifically, IoT sensors deployed in olive groves monitor critical environmental conditions that affect cultivation, such as soil moisture, temperature, and humidity, capturing the type of real-time data that is fundamental to PA [176,179]. During harvesting, processing, transport and storage, IoT sensors track vital parameters. For example, temperature sensors ensure optimal conditions for quality preservation [56,168]. The data captured by this sensor network is transmitted, often via gateways such as Raspberry Pi [176,177], and immutably recorded on the blockchain, creating a verifiable audit trail [56,175].

Otherwise, Radio Frequency Identification (RFID) or Near Field Communication (NFC) tags attached to crates, tanks or bottles allow for seamless tracking of batches throughout the chain [170,180,181]. In addition, technologies such as Global Positioning System (GPS) provide precise location information that is critical for verifying geographic origin [176], while DNA-based technologies are key for authenticating varietal origin [102]. Furthermore, advanced analytical techniques such as Nuclear Magnetic Resonance (NMR) [171] and Differential Scanning Calorimetry (DSC) [182] are used for quality control and authenticity checks, such as verifying geographic or varietal origin, and generate detailed data profiles suitable for compilation into databases to support traceability systems.

The successful implementation of such systems depends on making the wealth of traceability information easily accessible to all stakeholders, especially the end consumer. Mobile technologies, especially smartphones, are the main channel for this interaction [181,183]. By scanning QR codes [180] or tapping NFC tags [181] on EVOO bottle labels, consumers can access detailed product histories via user-friendly mobile apps or web interfaces [175,183]. This includes verifiable details about the origin of the oil, the specific varieties used, processing methods, quality analyses, certifications (such as PDO/PGI (Protected Geographical Indication) or organic), and the journey through the supply chain. This direct link to verified information enables consumers to make more informed purchasing decisions and significantly increases their trust in the brand [168,169,184]. The EVO NFC system demonstrates how standard smartphone NFC capabilities can facilitate this interaction seamlessly across the chain [181]. At the same time, supply chain operators can use similar interfaces for efficient data entry, batch tracking and process management [170,183].

The synergistic combination of the secure ledger of blockchain, the real-time data collection of IoT, the automation of smart contracts, and the user-friendly access of mobile/web technology offers a potentially transformative ecosystem for OOSC traceability. This integrated digital approach offers significant benefits: it increases transparency and visibility from grove to consumer [40,56,168]; improves food safety and quality assurance through continuous monitoring and immutable records [56,167,168]; significantly deters fraud and adulteration by making product history verifiable [40,56,168]; increases operational efficiency by automating processes such as quality control and reducing manual intervention [56,168]; builds consumer trust and adds brand value by demonstrating authenticity and quality [56,169,184]; and can support compliance with regulations and certifications through robust, documented evidence [40,167,171].

While implementation challenges related to cost, standardisation, scalability and stakeholder adoption remain [40,174,178], the compelling benefits demonstrated in numerous studies and pilot projects strongly support the continued exploration and deployment of these digital tools for a safer, more transparent and ultimately more trusted olive oil industry.

4. Future outlook

The olive sector, steeped in tradition yet facing contemporary pressures, is on the cusp of a significant transformation, driven by the continued integration of digital and other 4.0 technologies. While the recent applications outlined in the previous section show considerable progress, the future trajectory points towards deeper integration, enhanced intelligence and a stronger focus on sustainability and resilience to address the multiple challenges outlined above, such as climate change impacts, resource scarcity, market demands for quality and transparency, and the need for economic viability, especially for smaller producers.

4.1. Improved precision, automation and resilience in farming

The development of PA and SF in olive groves is expected to accelerate, moving beyond current monitoring capabilities towards more predictive and prescriptive management. Future developments are likely to involve the synergistic fusion of data from different sources, including advanced RS platforms (satellites, UAVs) providing high-resolution spatial and temporal data [31,185,186], proximal sensors directly measuring plant physiological status [22,187,188] and IoT networks relaying real-time environmental data. The integration of proximal and RS data holds particular promise for more accurate, multi-scale assessments of water status [187], which is critical for optimising irrigation in the face of increasing drought stress exacerbated by climate change [18,189–191].

AI and ML will play a key role in translating this wealth of data into actionable insights. Future AI systems are expected to provide more sophisticated decision support to predict yield with greater accuracy [192], optimise inputs (water, nutrients) and enable earlier and more accurate detection and management of pests and diseases [31]. While AI shows promise for disease detection at the leaf level, significant advances are needed for reliable detection at the field level amidst environmental complexity [193]. Tackling devastating threats such as *Xylella fastidiosa* will require integrated approaches combining advanced RS (hyperspectral, thermal) with AI for early, pre-visual detection and epidemiological modelling to optimise surveillance and containment [37,39,194], alongside an understanding of vector ecology [21]. Similarly, smart monitoring systems for pests such as *Bactrocera oleae* will become more sophisticated [101].

RA will move beyond current harvesting aids (e.g. shakers) to more autonomous and complex operations. Future research is likely to focus on developing robots capable of selective harvesting based on maturity, precision pruning, targeted pest/disease treatment (reducing the use of chemicals) and autonomous navigation in difficult terrain [36,89]. Innovations such as endo-therapy, possibly combined with precision delivery systems, offer targeted treatment options for plant vascular diseases [195]. In addition, artificial pollination technologies could be used in specific scenarios to ensure fruit set [196]. The development of robotic orchard systems, such as narrow orchard designs, will facilitate the adoption of these technologies [197].

4.2. Improving quality control, authenticity and traceability

Ensuring the quality and authenticity of olive oil remains paramount, driven by consumer demand and the prevalence of fraud [13,78]. The future will see the continued development and deployment of rapid, non-destructive analytical techniques. Spectroscopic methods (NIR, MIR, Raman, fluorescence) and hyperspectral imaging will become more powerful, portable and integrated into online/inline monitoring systems within processing plants [104,109]. AI and chemometrics will be essential to extract meaningful information from the complex spectral data generated to improve the accuracy of quality assessment, geographical origin verification and adulteration detection [118,198,199]. Electronic sensing technologies, including e-noses and biosensors (potentially using nanotechnologies such as graphene [200]), will provide low-cost, real-time analysis capabilities for volatile profiles and specific biomarkers [132,133,201]. Techniques such as ion mobility spectrometry (IMS) also show potential for rapid analysis in food applications [202].

Traceability systems will evolve beyond simple record keeping to fully integrated, transparent and secure platforms. Blockchain technology, combined with IoT sensors for real-time monitoring and smart contracts for automated verification, is likely to become more widespread, although challenges related to scalability and adoption remain [40,56,174]. The integration of advanced analytical data (spectroscopy, DNA) on these platforms will provide robust, multi-layered proof of authenticity and quality from grove to consumer [102,203,204]. Advanced DNA-based techniques such as Droplet Digital Polymerase Chain Reaction (ddPCR) and Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) systems may offer improved accuracy for variety identification and fraud detection [204].

4.3. Driving sustainability, circularity and value creation

Addressing the environmental footprint of olive growing and processing is a critical future direction. Digital technologies will support efforts to optimise the use of resources (water, energy, agrochemicals) through precision management. A major focus will be the transition to a circular economy model for the olive sector [205]. This includes the comprehensive valorisation of by-products that are currently considered waste, such as olive mill wastewater (OMWW), olive pomace, leaves and pruning residues [24]. Future research will intensify efforts to efficiently extract high-value bioactive compounds (polyphenols such as oleuropein, hydroxytyrosol) from these streams for use in functional foods, nutraceuticals, pharmaceuticals and cosmetics [8,9,140,206]. These by-products also have potential for the production of biofuels, biopolymers (such as Polyhydroxyalkanoates (PHAs)), feed components, soil amendments and even building materials (e.g. olive stone ash in concrete) [207–209].

Nanotechnology offers promising ways to increase the value and application of olive derived products and by-products. This includes the development of nano-delivery systems to improve the bioavailability and efficacy of olive polyphenols for health applications [138,140,210, 211], the creation of nano-formulations for targeted plant protection or enhanced nutrient delivery (nano-fertilisers) [153,157,195], and the potential development of advanced food packaging materials [162]. However, the widespread adoption of nanotechnology requires a rigorous assessment of the potential environmental and health risks associated with nanomaterials, which calls for further research and clear regulatory frameworks [166,212,213].

4.4. Overcoming barriers to integration and adoption

Realising the full potential of these technologies depends on overcoming significant barriers to integration, data management and adoption (Fig. 3). Future efforts must focus on developing interoperable systems and common data standards to enable seamless communication between different technologies and platforms across the value chain [214]. In addition, handling the large datasets ("big data") common in PA requires advanced analytical tolos [68] and increasingly relies on ML and AI to process information and support management decisions through analysis and interpretation systems [36]. Robust data governance frameworks are needed to deal with the massive datasets being generated [215].

A key challenge is to ensure equitable access and adoption, especially for the many smallholders and cooperatives that dominate the sector, especially in traditional regions [11,14]. High investment costs, the need for digital literacy and technical skills, and potential resistance to change are significant barriers [40]. Future strategies must include the development of affordable and user-friendly solutions, the provision of targeted training and support, and the promotion of collaborative models (e.g. through cooperatives) to share costs and expertise [7,216]. Addressing cybersecurity risks, ensuring data privacy and the ethical use of AI will also be critical [35,172]. Ultimately, successful digital transformation will require a concerted effort involving researchers, technology providers, farmers, industry stakeholders and policymakers to create an enabling ecosystem that fosters innovation while ensuring sustainability, inclusivity and resilience for the future of the olive sector.

5. Conclusions

The olive sector, a globally significant industry with deep roots in tradition and culture, is at a critical juncture, facing a confluence of economic, environmental and market challenges. This review provides a comprehensive overview of the burgeoning role of digital and other 4.0 technologies in addressing these pressures and reshaping olive farming and industry. From cultivation to consumption, the integration of innovations such as PA, SF, IoT, AI/ML, robotics, AS (spectroscopy, HSI, biosensors), nanotechnology and blockchain offer transformative potential.

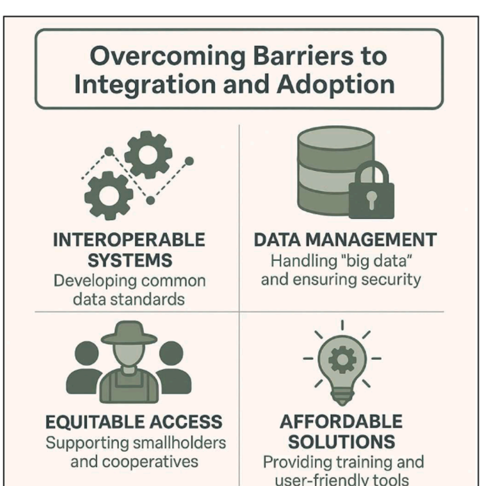

Fig. 3. Overcoming key barriers to digital transformation.

The analysis shows that these technologies are already delivering tangible benefits across the value chain. PA and SF tools are increasing resource efficiency (water, nutrients, pesticides), improving monitoring capabilities and enabling data-driven decision making in olive groves. AI and ML are proving instrumental in yield forecasting, early detection of pests and diseases, optimisation of processing parameters and, crucially, quality control and fraud detection. RA are beginning to alleviate labour shortages and improve the efficiency of harvesting and processing operations, while advanced spectroscopic and sensing methods are providing rapid, non-destructive tools to ensure the quality, authenticity and traceability of olive oil. Nanotechnology offers new ways to add value to olive products and by-products, particularly in nutraceutical and biomedical applications. In addition, blockchain integrated with IoT offers unprecedented levels of transparency and security, strengthening supply chain integrity and building consumer trust in a market often plagued by adulteration.

The future outlook points to accelerated adoption and deeper integration of these technologies. Synergistic approaches that combine data from multiple sources (RS, proximal sensors, IoT) and use sophisticated AI analytics will lead to more predictive, prescriptive and resilient agricultural systems that can adapt to the impacts of climate change and resource scarcity. Automation is likely to extend to more complex tasks, while quality control and traceability systems will become increasingly sophisticated, incorporating real-time data and advanced analytical fingerprints on secure platforms. An important future direction is to use these technologies to promote a circular economy within the sector, maximising the valorisation of by-products and minimising environmental impacts.

Despite the compelling potential, there are significant barriers to widespread adoption. High implementation costs, the need for increased digital literacy and technical skills, challenges related to data interoperability and management, and ensuring equitable access for smallholders and cooperatives remain critical barriers. Overcoming these will require concerted efforts focused on developing affordable, user-friendly solutions, providing targeted support and training, promoting collaborative models, and establishing robust data governance and cybersecurity frameworks.

In summary, digital and 4.0 technologies represent a paradigm shift for the olive sector. While not a panacea, their strategic and integrated application holds great promise for improving productivity, sustainability, quality and transparency throughout the value chain. Realising this potential will require continued research, innovation, investment and collaboration among all stakeholders to address the challenges and foster an inclusive transition towards a more resilient, competitive and trusted future for the global olive industry.

Ethics statement

Not applicable: This manuscript does not include human or animal research.

CRediT authorship contribution statement

Carlos Parra-López: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Saker Ben Abdallah:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Abdo Hassoun:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Sandeep Jagtap:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Funding acquisition, Formal analysis. **Guillermo Garcia-Garcia:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Data curation. **Tarek Ben Hassen:**

Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Hana Trollman:** Writing – original draft, Software, Resources, Investigation, Formal analysis, Data curation. **Frank Trollman:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Carmen Carmona-Torres:** Writing – review & editing, Writing – original draft, Supervision, Software, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] D. Langgut, R. Cheddadi, J.S. Carrión, M. Cavanagh, D. Colombaroli, W. J. Eastwood, R. Greenberg, T. Litt, A.M. Mercuri, A. Miebach, C.N. Roberts, H. Woldring, J. Woodbridge, The origin and spread of olive cultivation in the Mediterranean Basin: the fossil pollen evidence, Holocene 29 (5) (2019) 902–922.

[2] S. Ben Abdallah, C. Parra-López, S. Elfkih, E.M. Suárez-Rey, M. Romero-Gámez, Sustainability assessment of traditional, intensive and highly-intensive olive growing systems in Tunisia by integrating life cycle and Multicriteria Decision analyses, Sustain. Prod. Consum. 33 (2022) 73–87.

[3] M. Torres, P. Pierantozzi, P. Searles, M.C. Rousseaux, G. García-Inza, A. Miserere, R. Bodoira, C. Contreras, D. Maestri, Olive cultivation in the Southern Hemisphere: flowering, water requirements and oil quality responses to new crop environments, Front. Plant Sci. 8 (2017).

[4] Z. Wiesman, The History of Olive Oil Cultivation in the Desert, in: Z. Wiesman (Ed.), Desert Olive Oil Cultivation, Academic Press, San Diego, 2009, pp. 55–63.

[5] IOC, International Workshop: carbon balance of the olive sector: part of the solution against climate change. https://www.internationaloliveoil.org/international-workshop-carbon-balance-of-the-olive-sector-part-of-the-solution-against-climate-change, 2023. https://www.internationaloliveoil.org/international-workshop-carbon-balance-of-the-olive-sector-part-of-the-solution-against-climate-change.

[6] C. Parra-López, L. Reina-Usuga, G. Garcia-Garcia, C. Carmona-Torres, Functional analysis of technological innovation systems enabling digital transformation: a semi-quantitative multicriteria framework applied in the olive sector, Agric Syst 214 (2024) 103848.

[7] L. Reina-Usuga, C. Parra-López, P. Sánchez-Zamora, C. Carmona-Torres, Towards socio-digital rural territories to drive digital transformation: general conceptualisation and application to the olive areas of Andalusia, Spain, Geoforum. 145 (2023) 103827.

[8] S. Filardo, M. Roberto, D. Di Risola, L. Mosca, M. Di Pietro, R. Sessa, Olea europaea L-derived secoiridoids: beneficial health effects and potential therapeutic approaches, Pharmacol. Ther. 254 (2024).

[9] C.S.A. Monteiro, I.A. Adedara, E.O. Farombi, T. Emanuelli, Nutraceutical potential of olive pomace: insights from cell-based and clinical studies, J. Sci. Food Agric. 104 (7) (2024) 3807–3815.

[10] M.A. Martinez-Gonzalez, A.H. Hernandez, Effect of the Mediterranean diet in cardiovascular prevention, Rev. Esp. Cardiol. 77 (7) (2024) 574–582.

[11] B. Bernardi, G. Falcone, T. Stillitano, S. Benalia, A. Strano, J. Bacenetti, A.I. De Luca, Harvesting system sustainability in Mediterranean olive cultivation, Science of The Total Environment 625 (2018) 1446–1458.

[12] F. Abid, B. Kaffel, The extent of virgin olive-oil prices' distribution revealing the behavior of market speculators, Review of Quantitative Finance and Accounting 50 (2) (2018) 561–590.

[13] M. Meenu, Q. Cai, B. Xu, A critical review on analytical techniques to detect adulteration of extra virgin olive oil, Trends. Food Sci. Technol. 91 (2019) 391–408.

[14] C. Parra-López, L. Reina-Usuga, C. Carmona-Torres, S. Sayadi, L. Klerkx, Digital transformation of the agrifood system: quantifying the conditioning factors to inform policy planning in the olive sector, Land. use policy. 108 (May) (2021), 105537–105537.

[15] C. Carmona-Torres, C. Parra-López, S. Sayadi, M. Chirosa-Ríos, A public/private benefits framework for the design of polices oriented to sustainability in agriculture: an application to olive growing, Land. use policy. 58 (2016) 54–69.

[16] S. Ben Abdallah, S. Elfkih, E.M. Suárez-Rey, C. Parra-López, M. Romero-Gámez, Evaluation of the environmental sustainability in the olive growing systems in Tunisia, J. Clean. Prod. 282 (2021) 124526.

[17] C. Carmona-Torres, C. Parra-López, S. Sayadi, L. Reina-Usuga, Abandonment factors and alternatives in sloping olive growing: the case of Andalusia, Spain, Land. use policy. 132 (2023) 106836.

[18] I.J. Lorite, C. Gabaldón-Leal, M. Ruiz-Ramos, A. Belaj, R. de la Rosa, L. León, C. Santos, Evaluation of olive response and adaptation strategies to climate change under semi-arid conditions, Agric. Water. Manage 204 (2018) 247–261.

[19] M.C. Dias, M. Araujo, S. Silva, C. Santos, Sustainable olive culture under climate change: the potential of biostimulants, Horticulturae 8 (11) (2022).

[20] M. Gratsea, K.V. Varotsos, J. López-Nevado, S. López-Feria, C. Giannakopoulos, Assessing the long-term impact of climate change on olive crops and olive fly in Andalusia, Spain, through climate indices and return period analysis, Clim. Serv. 28 (2022) 100325.

[21] N. Bodino, V. Cavalieri, C. Dongiovanni, M. Saponari, D. Bosco, Bioecological traits of spittlebugs and their implications for the epidemiology and control of the Xylella fastidiosa epidemic in Apulia (Southern Italy), Phytopathology. 113 (9) (2023) 1647–1660.

[22] G. Noun, M. Lo Cascio, D. Spano, S. Marras, C. Sirca, Plant-based methodologies and approaches for estimating Plant water status of Mediterranean tree species: a semi-systematic review, Agronomy-Basel 12 (9) (2022).

[23] M. Romero-Gámez, J. Castro-Rodríguez, E.M. Suárez-Rey, Optimization of olive growing practices in Spain from a life cycle assessment perspective, J. Clean. Prod. 149 (2017) 25–37.

[24] J.M. Ochando Pulido, A review on the use of membrane technology and fouling control for olive mill wastewater treatment, Science of the Total Environment 563 (2016) 664–675.

[25] F. da Silveira, F.H. Lermen, F.G. Amaral, An overview of agriculture 4.0 development: systematic review of descriptions, technologies, barriers, advantages, and disadvantages, Comput. Electron. Agric. 189 (2021).

[26] A. Hassoun, Food Industry 4.0: Emerging Trends and Technologies in Sustainable Food Production and Consumption, Elsevier, 2024.

[27] H. Trollman, F. Bader, Y. Luo, G. Garcia-Garcia, S. Jagtap, C. Parra-López, J. A. Colwill, F. Trollman, Food safety 4.0, in: A. Hassoun (Ed.), Food Industry 4.0: Emerging Trends and Technologies in Sustainable Food Production and Consumption, Elsevier, 2024, p. 320.

[28] C. Parra-López, S. Ben Abdallah, G. Garcia-Garcia, A. Hassoun, P. Sánchez-Zamora, H. Trollman, S. Jagtap, C. Carmona-Torres, Integrating digital technologies in agriculture for climate change adaptation and mitigation: state of the art and future perspectives, Comput. Electron. Agric. 226 (2024) 109412.

[29] A. Hassoun, S. Jagtap, H. Trollman, G. Garcia-Garcia, L.N.K. Duong, P. Saxena, Y. Bouzembrak, H. Treiblmaier, C. Parra-López, C. Carmona-Torres, K. Dev, D. Mhlanga, A. Aït-Kaddour, From Food Industry 4.0 to Food Industry 5.0: identifying technological enablers and potential future applications in the food sector, Compr. Rev. Food Sci. Food Saf. 23 (6) (2024) e370040.

[30] M. Biocca, P. Gallo, S. Canali, E. Testani, Digital technologies for the sustainable management of the olive orchards in Central Italy: the farmers' Perception, in: V. Ferro, G. Giordano, S. Orlando, M. Vallone, G. Cascone, S.M.C. Porto (Eds.), AIIA 2022: Biosystems Engineering Towards the Green Deal, Springer International Publishing, Cham, 2023, pp. 353–361.

[31] P. Marques, L. Padua, J.J. Sousa, A. Fernandes-Silva, Advancements in remote sensing imagery applications for precision management in Olive growing: a systematic review, Remote Sens. (Basel) 16 (8) (2024).

[32] M. Perez-Ruiz, P. Gonzalez-de-Santos, A. Ribeiro, C. Fernandez-Quintanilla, A. Peruzzi, M. Vieri, S. Tomic, J. Agueera, Highlights and preliminary results for autonomous crop protection, Comput. Electron. Agric. 110 (2015) 150–161.

[33] S.P. Garofalo, V. Giannico, L. Costanza, S.A. Ali, S. Camposeo, G. Lopriore, F. P. Salcedo, G.A. Vivaldi, Prediction of stem water potential in olive orchards using high-resolution planet satellite images and machine learning techniques, Agronomy-Basel 14 (1) (2024).

[34] I. Pocas, A. Calera, I. Campos, M. Cunha, Remote sensing for estimating and mapping single and basal crop coefficientes: a review on spectral vegetation indices approaches, Agric. Water. Manage 233 (2020).

[35] C. Parra-López, L. Reina-Usuga, G. Garcia-Garcia, C. Carmona-Torres, Designing policies to promote the adoption of digital phytosanitation towards sustainability: the case of the olive sector in Andalusia, Agric Syst 221 (2024) 104147.

[36] E. Roma, P. Catania, Precision oliviculture: research topics, challenges, and opportunities-A review, Remote Sens. (Basel) 14 (7) (2022).

[37] M.P. Velasco-Amo, A. Vicent, P.J. Zarco-Tejada, J.A. Navas-Cortes, B.B. Landa, Recent research accomplishments on early detection of*Xylellafastidiosa*outbreaks in the Mediterranean Basin, Phytopathol. Mediterr. 61 (3) (2022) 549–561.

[38] R.A. Diaz-Varela, R. de la Rosa, L. Leon, P.J. Zarco-Tejada, High-resolution airborne UAV imagery to assess olive tree crown parameters using 3D photo reconstruction: application in breeding trials, Remote Sens. (Basel) 7 (4) (2015) 4213–4232.

[39] P.J. Zarco-Tejada, C. Camino, P.S.A. Beck, R. Calderon, A. Hornero, R. Hernandez-Clemente, T. Kattenborn, M. Montes-Borrego, L. Susca, M. Morelli, V. Gonzalez-Dugo, P.R.J. North, B.B. Landa, D. Boscia, M. Saponari, J.A. Navas-Cortes, Previsual symptoms of Xylella fastidiosa infection revealed in spectral plant-trait alterations, Nat. Plants. 4 (7) (2018) 432–439.

[40] G. Chiaraluce, D. Bentivoglio, A. Finco, M. Fiore, F. Conto, A. Galati, Exploring the role of blockchain technology in modern high-value food supply chains: global trends and future research directions, Agric. Econ. 12 (1) (2024).

[41] R. Castro-Munoz, G. Boczkaj, E. Gontarek, A. Cassano, V. Fila, Membrane technologies assisting plant-based and agro-food by-products processing: a comprehensive review, Trends. Food Sci. Technol. 95 (2020) 219–232.

[42] N. Vidakis, M. Petousis, D. Kalderis, N. Michailidis, E. Maravelakis, V. Saltas, N. Bolanakis, V. Papadakis, M. Spiridaki, A. Argyros, Reinforced HDPE with optimized biochar content for material extrusion additive manufacturing: morphological, rheological, electrical, and thermomechanical insights, Biochar. 6 (1) (2024).

[43] J. Rubio-Delgado, C.J. Pérez, M.A. Vega-Rodríguez, Predicting leaf nitrogen content in olive trees using hyperspectral data for precision agriculture, Precis. Agric. 22 (1) (2021) 1–21.
[44] A. Nappa, M. Quartulli, I. Azpiroz, S. Marchi, D. Guidotti, M. Staiano, R. Siciliano, Probabilistic Bayesian Neural networks for olive phenology prediction in precision agriculture, Ecol. Inform. 82 (2024) 102723.
[45] A. Massaoudi, A. Berguiga, A. Harchay, Secure irrigation system for olive orchards using internet of things, Cmc-Computers Materials & Continua 72 (3) (2022) 4663–4673.
[46] A. Massaoudi, A. Berguiga, A. Harchay, M. Ben Ayed, H. Belmabrouk, Spectral and Energy Efficiency Trade-Off in UAV-Based Olive Irrigation Systems, Applied Sciences (2023).
[47] A. Ksibi, M. Ayadi, B.O. Soufiene, M.M. Jamjoom, Z. Ullah, MobiRes-Net: a hybrid deep learning model for detecting and classifying olive leaf diseases, Applied Sciences (2022).
[48] A. Moreno, A.J. Rescia, S. Pascual, M. Ortega, Methodological approach to spatial analysis of agricultural pest dispersal in olive landscapes, Environ. Monit. Assess. 194 (6) (2022) 411.
[49] D.E. Tsesmelis, I. Gkotsis, C. Saltogiannis, S. Reppas, S. Panagakis, E. Zervas, An integrated approach of carbon footprint calculation for agricultural sector through smart-farming, J. Clean. Prod. 486 (2025) 144556.
[50] C. Albu, A. Chira, A. Stoica, G.-L. Radu, A. Radoi, M. Stoian, O.-G. Simionescu, S. A.V. Eremia, N-doped nanocrystalline graphite electrochemical sensor for oleuropein detection from extra Virgin olive oils, Chemosensors (2024).
[51] F. Venturini, M. Sperti, U. Michelucci, I. Herzig, M. Baumgartner, J.P. Caballero, A. Jimenez, M.A. Deriu, Exploration of Spanish olive oil quality with a miniaturized low-cost fluorescence sensor and machine learning techniques, Foods. (2021).
[52] Z. Viskadourakis, A. Theodosi, K. Katsara, M. Sevastaki, G. Fanourakis, O. Tsilipakos, V.M. Papadakis, G. Kenanakis, Engraved split-ring resonators as potential microwave sensors for olive oil quality control, ACS. Appl. Electron. Mater. 6 (5) (2024) 3846–3856.
[53] S. Atalla, S. Tarapiah, A. Gawanmeh, M. Daradkeh, H. Mukhtar, Y. Himeur, W. Mansoor, K.F. Hashim, M. Daadoo, IoT-enabled precision agriculture: developing an ecosystem for optimized crop management, information, 2023.
[54] A. Lucas Pascual, A. Madueño Luna, M. de Jódar Lázaro, J.M. Molina Martínez, A. Ruiz Canales, J.M. Madueño Luna, M. Justicia Segovia, Analysis of the functionality of the feed chain in olive pitting, slicing and stuffing machines by IoT, Computer Vision and neural network diagnosis, Sensors (2020).
[55] A. Alsayat, H. Ahmadi, Workers' Opinions on using the internet of things to enhance the performance of the olive oil industry: a machine learning approach, processes, 2023.
[56] V. Vitaskos, K. Demestichas, S. Karetsos, C. Costopoulou, Blockchain and internet of things technologies for food traceability in olive oil supply chains, Sensors (2024).
[57] F. Lima, R. Blanco-Sepúlveda, D. Andújar, Mapping and quantifying medium-term soil loss rates in mountain olive groves using unmanned aerial vehicle technology, MethodsX. 12 (2024) 102786.
[58] R. Sarabia, A. Aquino, J.M. Ponce, G. López, J.M. Andújar, Automated identification of crop tree crowns from UAV multispectral imagery by means of morphological image analysis, Remote Sens. (Basel) (2020).
[59] E. Guermazi, A. Wali, M. Ksibi, Combining remote sensing, SPAD readings, and laboratory analysis for monitoring olive groves and olive oil quality, Precis. Agric. 25 (1) (2024) 65–82.
[60] C. Lin, J. Zhou, L. Yin, R. Bouabid, D. Mulla, E. Benami, Z. Jin, Sub-national scale mapping of individual olive trees integrating Earth observation and deep learning, ISPRS Journal of Photogrammetry and Remote Sensing 217 (2024) 18–31.
[61] R. Brigante, V. Baiocchi, R. Calisti, L. Marconi, P. Proietti, F. Radicioni, L. Regni, A. Vinci, GIS-based approach for estimating olive tree heights using high-resolution satellite imagery and shadow analysis, Applied Sciences (2025).
[62] S. Tsiaras, C. Domakinis, Use of GIS in selecting suitable tree crop cultivation sites in mountainous less favoured areas: an example from Greece, Forests. (2023).
[63] G. Modica, M. Pollino, G. Messina, S. Lanucara, S. Praticò, Web-based multicriteria spatial decision support system (MC-SDSS) for land suitability evaluation in olive groves. A case study in Calabria region, southern Italy, Agric Syst 228 (2025) 104375.
[64] A. Sghaier, H. Dhaou, L. Jarray, Z. Abaab, A. Sekrafi, M. Ouessar, Assessment of drought stress in arid olive groves using HidroMORE model, Journal of Agricultural Engineering 53 (1) (2022).
[65] N.N. Kourgialas, A. Hliaoutakis, A.V. Argyriou, G. Morianou, A.E. Voulgarakis, E. Kokinou, I.N. Daliakopoulos, D. Kalderis, K. Tzerakis, G. Psarras, N. Papadopoulos, T. Manios, A. Vafidis, P. Soupios, A web-based GIS platform supporting innovative irrigation management techniques at farm-scale for the Mediterranean island of Crete, Science of the Total Environment 842 (2022) 156918.
[66] L. Sánchez-Fernández, M. Barrera, J. Martínez-Guanter, M. Pérez-Ruiz, Drift reduction in orchards through the use of an autonomous UAV system, Comput. Electron. Agric. 211 (2023) 107981.
[67] L. Sánchez-Fernández, M. Barrera-Báez, J. Martínez-Guanter, M. Pérez-Ruiz, Reducing environmental exposure to PPPs in super-high density olive orchards using UAV sprayers, Front. Plant Sci. 14 (2024).
[68] Z. Moumen, I. Elhassnaoui, W. Khaddi, M.A.S. Wahba, A. Lahrach, Assessment of deficit irrigation efficiency. Case study: middle Sebou and Innaouene downstream, Open. Agric. 6 (1) (2021) 102–114.
[69] M.I. Sánchez-Rodríguez, E.M. Sánchez-López, A. Marinas, J.M. Caridad, F. J. Urbano, Correlation structure between agroclimatic big data and EVOO fatty acid profile determined by GC and NMR spectra, J. Chemom. 34 (8) (2020) e3273.
[70] J.J. Cubillas, M.I. Ramos, J.M. Jurado, F.R. Feito, A machine learning model for early prediction of crop yield, nested in a web application in the cloud: a case study in an olive grove in southern Spain, Agriculture (2022).
[71] J.L. Gonzalez-Andujar, Expert system for pests, diseases and weeds identification in olive crops, Expert. Syst. Appl. 36 (2) (2009) 3278–3283.
[72] P. Bocca, A. Orellana, C. Soria, R. Carelli, On field disease detection in olive tree with vision systems, Array 18 (2023) 100286.
[73] H.H. Alshammari, A.I. Taloba, O.R. Shahin, Identification of olive leaf disease through optimized deep learning approach, Alexandria Engineering Journal 72 (2023) 213–224.
[74] S.N. Al-khateeb, An AI-based framework for Olive disease identification using SqueezeNet, artificial Neural networks, and support Vector machines, in: 2024 IEEE 30th International Conference on Telecommunications (ICT), 2024, pp. 01–05.
[75] J. Mendes, J. Lima, L.A. Costa, N. Rodrigues, P. Leitão, A.I. Pereira, An artificial intelligence-based method to identify the stage of maturation in olive oil mills, in: A.I. Pereira, A. Mendes, F.P. Fernandes, M.F. Pacheco, J.P. Coelho, J. Lima (Eds.), Optimization, Learning Algorithms and Applications, Springer Nature Switzerland, Cham, 2024, pp. 63–77.
[76] J. Lozano-Castellón, A. Olmo-Cunillera, E. Casadei, E. Valli, I. Domínguez-López, E. Miliarakis, M. Pérez, A. Ninot, A. Romero-Aroca, A. Bendini, R.M. Lamuela-Raventós, A. Vallverdú-Queralt, A targeted foodomic approach to assess differences in extra virgin olive oils: effects of storage, agronomic and technological factors, Food Chem. 435 (2024) 137539.
[77] R. Aroca-Santos, J.C. Cancilla, E.S. Pariente, J.S. Torrecilla, Neural networks applied to characterize blends containing refined and extra virgin olive oils, Talanta 161 (2016) 304–308.
[78] A. Sudhakar, S.K. Chakraborty, N.K. Mahanti, C. Varghese, Advanced techniques in edible oil authentication: a systematic review and critical analysis, Crit. Rev. Food Sci. Nutr. 63 (7) (2021) 873–901.
[79] N.S. Brilhante, H.R. Bizzo, A. Caratti, S. Squara, C. Cordero, Artificial intelligence tools and concepts give access to authenticity and quality information in Brazilian olive oil volatilome, Journal of Food Composition and Analysis 136 (2024) 106826.
[80] J.T. Colmenero-Martinez, G.L. Blanco-Roldán, S. Bayano-Tejero, F.J. Castillo-Ruiz, R.R. Sola-Guirado, J.A. Gil-Ribes, An automatic trunk-detection system for intensive olive harvesting with trunk shaker, Biosyst. Eng. 172 (2018) 92–101.
[81] G. Messina, M. Sbaglia, B. Bernardi, Mechanical harvesting of olive orchards: an overview on trunk shakers, AgriEngineering (2025).
[82] R.R. Sola-Guirado, D. Ceular-Ortiz, J.A. Gil-Ribes, Automated system for real time tree canopy contact with canopy shakers, Comput. Electron. Agric. 143 (2017) 139–148.
[83] G.S. Berger, M. Teixeira, A. Cantieri, J. Lima, A.I. Pereira, A. Valente, G.G. D. Castro, M.F. Pinto, Cooperative heterogeneous robots for autonomous insects trap monitoring system in a precision agriculture scenario, Agriculture 13 (2) (2023) a.
[84] G.S. Berger, L.B. Junior, M.F. Pinto, A.O. Júnior, J. Mendes, Y.M. da Silva, A. I. Pereira, A. Valente, J. Lima, UAV-assisted navigation for insect traps in olive groves, in: Sixth Iberian Robotics conference, Springer, Cham, 2023, pp. 86–97, b.
[85] F.A. Auat Cheein, G. Scaglia, M. Torres-Torriti, J. Guivant, A.J. Prado, J. Arnò, A. Escolà, J.R. Rosell-Polo, Algebraic path tracking to aid the manual harvesting of olives using an automated service unit, Biosyst. Eng. 142 (2016) 117–132.
[86] F. Penizzotto, E. Slawinski, V. Mut, Laser radar based autonomous mobile robot guidance system for Olive Groves navigation, IEEE Latin America Transactions 13 (5) (2015) 1303–1312.
[87] A. Khan, Z. Haq, M. Islam, A. Saad, E.S. Raza, I. Ali, K. Sheraz, M. Usman, M. M. Ali, M. Ali, Prospects and scope of Olive mechanization: a review, Zoo Botanica 1 (2024).
[88] F.A. Auat Cheein, D. Herrera, J. Gimenez, R. Carelli, M. Torres-Torriti, J.R. Rosell-Polo, A. Escolà, J. Arnó, Human-robot interaction in precision agriculture: sharing the workspace with service units, in: 2015 IEEE International conference on industrial technology (ICIT), IEEE, 2015, pp. 289–295.
[89] S. Fountas, N. Mylonas, I. Malounas, E. Rodias, C. Hellmann Santos, E. Pekkeriet, Agricultural Robotics for field operations, Sensors (2020).
[90] A. Aljaafreh, E.Y. Elzagzoug, J. Abukhait, A.-H. Soliman, S.S. Alja'Afreh, A. Sivanathan, J. Hughes, A real-time olive fruit detection for harvesting robot based on YOLO algorithms, Acta Technologica Agriculturae 26 (3) (2023) 121–132.
[91] G. Salvucci, F. Pallottino, L. De Laurentiis, F. Del Frate, R. Manganiello, F. Tocci, S. Vasta, S. Figorilli, B. Bassotti, S. Violino, L. Ortenzi, Fast olive quality assessment through RGB images and advanced convolutional neural network modeling, European Food Research and Technology 248 (5) (2022) 1395–1405.
[92] R.R. Sola-Guirado, S. Bayano-Tejero, F. Aragón-Rodríguez, B. Bernardi, S. Benalia, S. Castro-García, A smart system for the automatic evaluation of green olives visual quality in the field, Comput. Electron. Agric. 179 (2020) 105858.
[93] L. Ortenzi, S. Figorilli, C. Costa, F. Pallottino, S. Violino, M. Pagano, G. Imperi, R. Manganiello, B. Lanza, F. Antonucci, A machine vision rapid method to determine the ripeness degree of olive lots, Sensors 21 (9) (2021) 2940, p.. 21(9).
[94] R. Manganiello, M. Pagano, R. Ciccoritti, M. Cecchini, C. Cedrola, P. Mattei, R. Tomasone, Innovative device for automated monitoring of table olive fermentation parameters: first experimental results, Machines 11 (8) (2023) 771.

[95] P. Cano Marchal, S. Satorres Martínez, J.Gómez Ortega, J.Gámez García, Automatic system for the detection of defects on olive fruits in an oil mill, Applied Sciences (2021).
[96] M. Waleed, T.W. Um, A. Khan, Z. Ahmad, An automated method for detection and enumeration of olive trees through remote sensing, IEEe Access. 8 (2020) 108592–108601.
[97] F. Crocetti, E. Bellocchio, A. Dionigi, S. Felicioni, G. Costante, M.L. Fravolini, P. Valigi, ARD-VO: agricultural robot data set of vineyards and olive groves, J. Field. Robot. 40 (6) (2023) 1678–1696.
[98] A. Aquino, J.M. Ponce, J.M. Andújar, Identification of olive fruit, in intensive olive orchards, by means of its morphological structure using convolutional neural networks, Comput. Electron. Agric. 176 (2020) 105616.
[99] Y. Karabatis, X. Lin, N.J. Sanket, M.G. Lagoudakis, Y. Aloimonos, Detecting olives with synthetic or real data? Olive the above, in: 2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2023, pp. 4242–4249.
[100] B. Rey, N. Aleixos, S. Cubero, J. Blasco, Xf-Rovim. A field robot to detect olive trees infected by Xylella Fastidiosa using proximal sensing, Remote Sens. (Basel) 11 (3) (2019) 221.
[101] O.S. Arvaniti, E. Rodias, A. Terpou, N. Afratis, G. Athanasiou, T. Zahariadis, Bactrocera oleae control and smart farming technologies for olive orchards in the context of optimal olive oil quality: a review, Agronomy-Basel 14 (11) (2024).
[102] R. Ben Ayed, M. Hanana, S. Ercisli, R. Karunakaran, A. Rebai, F. Moreau, Integration of innovative technologies in the agri-food sector: the fundamentals and practical case of DNA-based traceability of olives from fruit to oil, Plants (2022).
[103] D.M. Gila, D.A. Puerto, J.G. Garcia, J.G. Ortega, Automatic classification of olives for oil production using computer vision, in: IEEE International Conference on Industrial Technology (ICIT), IEEE, 2015, pp. 1651–1656.
[104] A. Cappelli, S. Cividino, V. Redaelli, G. Tripodi, G. Aiello, S. Velotto, M. Zaninelli, Applying spectroscopies, imaging analyses, and other non-destructive techniques to olives and extra Virgin olive oil: a systematic review of current knowledge and future applications, Agriculture-Basel 14 (7) (2024).
[105] X. Li, L. Zhang, Y. Zhang, D. Wang, X. Wang, L. Yu, W. Zhang, P. Li, Review of NIR spectroscopy methods for nondestructive quality analysis of oilseeds and edible oils, Trends. Food Sci. Technol. 101 (2020) 172–181.
[106] H.-J. He, M.V. da Silva Ferreira, Q. Wu, H. Karami, M. Kamruzzaman, Portable and miniature sensors in supply chain for food authentication: a review, Crit. Rev. Food Sci. Nutr. (2024) 1–21.
[107] L.P. Foli, M.C. Hespanhol, K.A.M.L. Cruz, C. Pasquini, Miniaturized near-infrared spectrophotometers in forensic analytical science — a critical review, Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy 315 (2024) 124297.
[108] R. Reda, T. Saffaj, I. Bouzida, O. Saidi, M. Belgrir, B. Lakssir, E.M. El Hadrami, Optimized variable selection and machine learning models for olive oil quality assessment using portable near infrared spectroscopy, Spectrochim. Acta a Mol. Biomol. Spectrosc. 303 (2023) 123213.
[109] A. Arroyo-Cerezo, X. Yang, A.M. Jiménez-Carvelo, M. Pellegrino, A. Felicita Savino, P. Berzaghi, Assessment of extra virgin olive oil quality by miniaturized near infrared instruments in a rapid and non-destructive procedure, Food Chem. 430 (2024) 137043.
[110] C. Melendreras, A. Soldado, J.M. Costa-Fernández, A. López, M. Valledor, J. C. Campo, F. Ferrero, An affordable NIR spectroscopic system for fraud detection in olive oil, Sensors 23 (3) (2023) 1728.
[111] N. Vanstone, A. Moore, P. Martos, S. Neethirajan, Detection of the adulteration of extra virgin olive oil by near-infrared spectroscopy and chemometric techniques, Food Quality and Safety 2 (4) (2018) 189–198.
[112] E. Mendes, N. Duarte, Mid-infrared spectroscopy as a valuable tool to tackle food analysis: a literature review on coffee, dairies, honey, olive oil and wine, foods, 2021.
[113] C. Gardeli, S. Sykioti, G. Exarchos, M. Koliatsou, P. Andritsos, E.Z. Panagou, The differentiation of extra Virgin olive oil from other olive oil categories based on FTIR spectroscopy and random forest, Applied Sciences (2025).
[114] A. Lobo-Prieto, N. Tena, R. Aparicio-Ruiz, D.L. García-González, E. Sikorska, Monitoring Virgin olive oil shelf-life by fluorescence spectroscopy and sensory characteristics: a multidimensional study carried out under simulated market conditions, Foods. (2020).
[115] F. Venturini, S. Fluri, M. Mejari, M. Baumgartner, D. Piga, U. Michelucci, Shedding light on the ageing of extra virgin olive oil: probing the impact of temperature with fluorescence spectroscopy and machine learning techniques, Lwt-Food Science and Technology 191 (2024) 115679.
[116] Y. El Morabit, M. El Maadoudi, N. Alahlah, H. Amhamdi, A. Salhi, M.h. Ahari, Detection and quantification of olive oil adulteration using fluorescence spectroscopy and chemometric tools, BIO Web Conf 109 (2024) 01016.
[117] Z. Lujun, C. Nuo, H. Xiaodong, F. Xinmin, G. Juanjuan, G. Jin, L. Sensen, W. Yan, W. Chunyan, Adulteration detection and quantification in olive oil using excitation-emission matrix fluorescence spectroscopy and chemometrics, J. Fluoresc. (2024).
[118] V.A. Lozano, A.M. Jiménez Carvelo, A.C. Olivieri, S.V. Kucheryavskiy, O. Y. Rodionova, A.L. Pomerantsev, Authentication of Argentinean extra-virgin olive oils using three-way fluorescence and two-way near-infrared data fused with multi-block DD-SIMCA, Food Chem. 463 (2025) 141127.
[119] R. Ríos-Reina, J.Á. Salatti-Dorado, C. Ortiz-Romero, M.J. Cardador, L. Arce, R. Callejón, A comparative study of fluorescence and raman spectroscopy for discrimination of virgin olive oil categories: chemometric approaches and evaluation against other techniques, Food Control 158 (2024) 110250.
[120] R. Kontzedaki, E. Orfanakis, G. Sofra-Karanti, K. Stamataki, A. Philippidis, A. Zoumi, M. Velegrakis, Verifying the geographical origin and authenticity of Greek olive oils by means of optical spectroscopy and multivariate analysis, Molecules. (2020).
[121] M. Bragolusi, A. Massaro, C. Zacometti, A. Tata, R. Piro, Geographical identification of Italian extra virgin olive oil by the combination of near infrared and raman spectroscopy: a feasibility study, J. Near. Infrared. Spectrosc. 29 (6) (2021) 359–365.
[122] I. Grigoletto, C. Cevoli, A. Koidis, T. Gallina Toschi, E. Valli, Infrared spectroscopy and chemometrics for predicting commercial categories of virgin olive oils and supporting the panel test, Food Res. Int. 199 (2025) 115347.
[123] F. Hashempour-baltork, S. Vali Zade, Y. Mazaheri, A. Mirza Alizadeh, H. Rastegar, Z. Abdian, M. Torbati, S.Azadmard Damirchi, Recent methods in detection of olive oil adulteration: state-of- the-art, J. Agric. Food Res. 16 (2024) 101123.
[124] T. Shi, T. Dai, T. Zhang, X. Ma, X. Wang, NMR spectroscopy combined with chemometrics for quality assessment of common vegetable oils: a review, Trends. Food Sci. Technol. 157 (2025) 104889.
[125] H. Alharbi, J. Kahfi, A. Dutta, M. Jaremko, A.-H. Emwas, The detection of adulteration of olive oil with various vegetable oils – A case study using high-resolution 700 MHz NMR spectroscopy coupled with multivariate data analysis, Food Control 166 (2024) 110679.
[126] E. Nanou, M. Bekogianni, T. Stamatoukos, S. Couris, Detection of adulteration of extra Virgin olive oil via laser-induced breakdown spectroscopy and ultraviolet-visible-near-infrared absorption spectroscopy: a comparative study, Foods. (2025).
[127] E. Nanou, N. Pliatsika, S. Couris, Rapid authentication and detection of olive oil adulteration using laser-induced breakdown spectroscopy, Molecules. (2023).
[128] G. Georgiou, P. Karvelis, C. Gogos, Computer vision-based detection and tracking in the olive sorting pipeline, in: D.D. Bochtis, D.E. Moshou, G. Vasileiadis, A. Balafoutis, P.M. Pardalos (Eds.), Information and Communication Technologies For Agriculture—Theme II: Data, Springer International Publishing, Cham, 2022, pp. 131–160.
[129] D. Malavi, A. Nikkhah, K. Raes, S. Van Haute, Hyperspectral imaging and chemometrics for authentication of extra Virgin olive oil: a comparative approach with FTIR, UV-VIS, Raman, and GC-MS, Foods. (2023).
[130] Z. Jiao, L. Song, Y. Zhang, J. Dai, Y. Liu, Q. Zhang, W. Qin, J. Yan, A comparative study of fluorescence hyperspectral imaging and FTIR spectroscopy combined with chemometrics for the detection of extra virgin olive oil adulteration, Journal of Food Measurement and Characterization (2024).
[131] P. Cano Marchal, D. Martínez Gila, J. Gámez García, J. Gómez Ortega, Expert system based on computer vision to estimate the content of impurities in olive oil samples, J. Food Eng. 119 (2) (2013) 220–228.
[132] A.V. Bounegru, C. Apetrei, Evaluation of olive oil quality with electrochemical sensors and biosensors: a review, Int. J. Mol. Sci. (2021).
[133] N. Rodrigues, N. Ferreiro, D. Ruano, F. Dias, A.C.A. Veloso, J.A. Pereira, A. M. Peres, Electronic nose: a tool to verify the PDO declaration of Portuguese olive oils, Journal of Food Measurement and Characterization 18 (4) (2024) 2952–2964.
[134] J.P. Navarro Soto, S.I. Rico, D.M. Martínez Gila, S.Satorres Martínez, Influence of the degree of fruitiness on the quality assessment of Virgin olive oils using electronic nose technology, Sensors (2024).
[135] G.G. Teixeira, L.G. Dias, N. Rodrigues, Í.M.G. Marx, A.C.A. Veloso, J.A. Pereira, A. M. Peres, Application of a lab-made electronic nose for extra virgin olive oils commercial classification according to the perceived fruitiness intensity, Talanta 226 (2021) 122122.
[136] A.V. Bounegru, C. Apetrei, Studies on the detection of oleuropein from extra Virgin olive oils using enzymatic biosensors, Int. J. Mol. Sci. (2022).
[137] N.-M. Christopoulou, V. Mamoulaki, A. Mitsiakou, E. Samolada, D.P. Kalogianni, T.K. Christopoulos, Screening method for the visual discrimination of olive oil from other vegetable oils by a multispecies DNA sensor, Anal. Chem. 96 (4) (2024) 1803–1811.
[138] U.G. Spizzirri, F. Aiello, G. Carullo, A. Facente, D. Restuccia, Nanotechnologies: an innovative tool to release natural extracts with antimicrobial properties, Pharmaceutics. 13 (2) (2021) 230.
[139] W.S. Alharbi, F.A. Almughem, A.M. Almehmady, S.J. Jarallah, W.K. Alsharif, N. M. Alzahrani, A.A. Alshehri, Phytosomes as an emerging nanotechnology platform for the topical delivery of bioactive phytochemicals, Pharmaceutics. 13 (9) (2021) 1475.
[140] I. De Luca, F. Di Cristo, A. Valentino, G. Peluso, A. Di Salle, A. Calarco, Food-derived bioactive molecules from Mediterranean diet: nanotechnological approaches and waste valorization as strategies to improve Human wellness, Polymers. (Basel) 14 (9) (2022).
[141] M. Gunawan, V. Boonkanokwong, Current applications of solid lipid nanoparticles and nanostructured lipid carriers as vehicles in oral delivery systems for antioxidant nutraceuticals: a review, Colloids and Surfaces B: Biointerfaces 233 (2024) 113608.
[142] M. Ashraf, H.S. El-Sawy, G.M. El Zaafarany, M.M.A. Abdel-Mottaleb, Can essential oils/botanical agents smart-nanoformulations Be the winning cards against psoriasis? Pharmaceutics. 15 (3) (2023) 750.
[143] H.S. Elsewedy, T.M. Shehata, M.M. Almostafa, W.E. Soliman, Hypolipidemic activity of olive oil-based nanostructured lipid carrier containing atorvastatin, Nanomaterials 12 (13) (2022) 2160.
[144] S.A. Navarro-Marchal, C. Griñán-Lisón, J.-M. Entrena, G. Ruiz-Alcalá, M. Tristán-Manzano, F. Martin, I. Pérez-Victoria, J.M. Peula-García, J.A. Marchal, Anti-CD44-conjugated olive oil liquid nanocapsules for targeting pancreatic cancer stem cells, Biomacromolecules. 22 (4) (2021) 1374–1388.

[145] H. Bakdi, N. Lenchi, S. Kebbouche-Gana, N.E. Djelali, Obtention of green-synthesized silver nanoparticles and evaluation of its antimicrobial and antifungal activity against skin pathogenic microorganisms, Biotecnología Aplicada 39 (4) (2022) 4201–4208.
[146] M.V.A. Confessor, M.A.A. Agreles, L.A.d.A. Campos, A.F. Silva Neto, J.C. Borges, R.M. Martins, A.M.L. Scavuzzi, A.C.S. Lopes, E.A.d.M. Kretzschmar, I.M. F. Cavalcanti, Olive oil nanoemulsion containing curcumin: antimicrobial agent against multidrug-resistant bacteria, Appl. Microbiol. Biotechnol. 108 (1) (2024) 241.
[147] S.A. Fahmy, A. Ramzy, A.M. Sawy, M. Nabil, M.Z. Gad, M. El-Shazly, M.A. M. Aboul-Soud, H.M.E.-S. Azzazy, Ozonated olive oil: enhanced cutaneous delivery via niosomal nanovesicles for melanoma treatment, Antioxidants 11 (7) (2022) 1318.
[148] T.H. Mahmood, A. Al-Samydai, M.A. Sulaibi, M. Alqaraleh, A.I. Abed, N. Shalan, A. Alsanabrah, S.T. Alsotari, H. Nsairat, W. Alshaer, Development of pegylated nano-phytosome formulation with oleuropein and rutin to compare anti-colonic cancer activity with Olea europaea leaves extract, Chem. Biodivers. 20 (8) (2023) e202300534.
[149] J.P.M. Ribeiro, D.J. Schebelski, A.M. Lyra, G.d.A. Camargo, J.M. Nadal, A. Novatski, J. Manfron, P.V. Farago, Physicochemical characterization, quantitative drug analysis, and stability testing of hydroxytyrosol-loaded poly (ε-caprolactone) nanocapsules, Brazilian Archives of Biology and Technology 66 (2023) e23230081.
[150] M. El Youssfi, A. Sifou, R. Ben Aakame, N. Mahnine, S. Arsalane, M. Halim, A. Laghzizil, A. Zinedine, Trace elements in foodstuffs from the Mediterranean Basin—Occurrence, risk assessment, Regulations, and prevention strategies: a review, Biol. Trace Elem. Res. 201 (5) (2023) 2597–2626.
[151] V. Basudkar, S.A. Gharat, M.M. Momin, M. Shringarpure, A review of anti-aging nanoformulations: recent developments in excipients for nanocosmeceuticals and regulatory guidelines, 39(3) (2022) 45–97.
[152] F.L. Tamashiro, M.N. Yukuyama, M.V.R. Velasco, G.L.B. De Araújo, N.A. Bou-Chacra, Nanoemulsions containing plant oils: how do they influence hair treatment? Int. J. Cosmet. Sci. 43 (2) (2021) 136–143.
[153] D. Schiavi, S. Francesconi, A.R. Taddei, E. Fortunati, G.M. Balestra, Exploring cellulose nanocrystals obtained from olive tree wastes as sustainable crop protection tool against bacterial diseases, Sci. Rep. 12 (1) (2022) 6149.
[154] S. Francesconi, V. Tagliavento, S. Ciarroni, F. Sestili, G.M. Balestra, Chitosan- and gallic acid-based (NPF) displayed antibacterial activity against three Pseudomonas spp. Plant pathogens and boosted systemic acquired resistance in kiwifruit and olive plants, Pest. Manage Sci. 80 (3) (2024) 1300–1313.
[155] R. Buonaurio, L. Almadi, F. Famiani, C. Moretti, G.E. Agosteo, L. Schena, Olive leaf spot caused by Venturia oleaginea: an updated review, Front. Plant Sci. 13 (2023).
[156] Z.Rohi Vishekaii, A. Soleimani, M. Ghasemnezhad, A. Hasani, The feasibility for replacement of urea with nitrogen nano-chelated fertilizer in olive (Olea europaea L.) orchards, Iranian Journal of Plant Physiology 10 (1) (2019) 3047–3058.
[157] L.F. Hagagg, N. Mustafa, M. Shahin, E.S. El-Hady, Impact of nanotechnology application on decreasing used rate of mineral fertilizers and improving vegetative growth of Aggizi olive seedlings, Bioscience research 15 (2) (2018) 1304–1311.
[158] O.M. Darwesh, S. Hassan, A. Abdellatif, Improve in vitro multiplication of olive shoots using environmental-safe chitosan, selenium, and silver nanostructures, Biointerface Res. Appl. Chem. 13 (5) (2023) 419–431.
[159] M.S. Hasanin, S.A.M. Hassan, A.M. AbdAllatif, O.M. Darwesh, Unveiling the silver lining: examining the effects of biogenic silver nanoparticles on the growth dynamics of in vitro olive shoots, Microb. Cell Fact. 23 (1) (2024) 79.
[160] L. Regni, D. Del Buono, M. Micheli, S.L. Facchin, C. Tolisano, P. Proietti, Effects of biogenic ZnO nanoparticles on growth, physiological, biochemical traits and antioxidants on olive tree In vitro, Horticulturae 8 (2) (2022) 161.
[161] A.F. Fath El-Bab, I.T. El-Ratel, A.-W.A. Abdel-Warith, E.M. Younis, S.J. Davies, A. A. El-Raghi, Investigating the impact of nanoemulsion of curcumin-loaded olive oil on growth performance, feed utilization, immunological responses, and redox status of Litopenaeus vannamei shrimp with emphasis on economic efficiency of supplementation, J. Anim. Physiol. Anim. Nutr. (Berl) 108 (6) (2024) 1877–1889.
[162] R.A. Trbojevich, S. Khare, J.-H. Lim, F. Watanabe, K. Gokulan, K. Krohmaly, K. Williams, Assessment of silver release and biocidal capacity from silver nanocomposite food packaging materials, Food and Chemical Toxicology 145 (2020) 111728.
[163] H. Ahari, L.K. Lahijani, Migration of silver and copper nanoparticles from food coating, Coatings 11 (4) (2021) 380.
[164] T. Mahjoub, S. Chernine, R. Lahmar, V. Gourain, M.-S. Mahjoub, A. Rejeb, M.-N. Romdane, S. Ben Romdhane, H. Abdelmelek, Silver nanoparticle-induced lymphocyte activation in zebrafish, Nanomedicine Research Journal 7 (2) (2022) 195–204.
[165] A. Sithole, S. Singh, Novel Applications of Silver-Nanoparticles in Food Contact material: A systematic Review, Universitat de Girona, 2024.
[166] M.M.V. Rao, N. Mohammad, S. Banerjee, P.K. Khanna, Synthesis and food packaging application of silver nano-particles: a review, Hybrid Advances 6 (2024) 100230.
[167] B. Zanoni, Extra-virgin olive oil traceability, the Extra-Virgin Olive Oil Handbook 2014, pp. 245–250.
[168] R. Alkhudary, X. Brusset, H. Naseraldin, P. Féniès, Enhancing the competitive advantage via Blockchain: an olive oil case study, IFAC-PapersOnLine 55 (2) (2022) 469–474.
[169] D.M. Consolaro, D.F. Uclés, J.V. Oya, Enhancing olive oil communication by blockchain agri-food traceability, New Medit: Mediterranean Journal of Economics, Agriculture and Environment= Revue Méditerranéenne d'Economie Agriculture et Environment 25 (1) (2025).
[170] M.E. Latino, M. Menegoli, M. Lazoi, A. Corallo, Voluntary traceability in food supply chain: a framework leading its implementation in Agriculture 4.0, Technol. Forecast. Soc. Change 178 (2022) 121564.
[171] C.R. Girelli, L. Del Coco, S. Zelasco, A. Salimonti, F.L. Conforti, A. Biagianti, D. Barbini, F.P. Fanizzi, Traceability of "Tuscan PGI" extra Virgin olive oils by 1H NMR metabolic profiles collection and analysis, Metabolites. (2018).
[172] C. Parra-López, L. Reina-Usuga, G. Garcia-Garcia, C. Carmona-Torres, Promoting digital traceability in agriculture: a predictive approach to adoption and policy design in the olive sector, Technol. Forecast. Soc. Change 215 (2025) 124077.
[173] A. Hassoun, S. Kamiloglu, G. Garcia-Garcia, C. Parra-López, H. Trollman, S. Jagtap, R.M. Aadil, T. Esatbeyoglu, Implementation of relevant fourth industrial revolution innovations across the supply chain of fruits and vegetables: a short update on traceability 4.0, Food Chem. 409 (2023) 135303.
[174] A. Pakseresht, S. Ahmadi Kaliji, K. Hakelius, Blockchain technology characteristics essential for the agri-food sector: a systematic review, Food Control 165 (2024) 110661.
[175] A. Arena, P. Bianchini, P. Perazzo, C. Vallati, G. Dini, BRUSCHETTA: an IoT blockchain-based framework for certifying extra Virgin olive oil supply chain, in: 2019 IEEE International Conference on Smart Computing (SMARTCOMP), 2019, pp. 173–179.
[176] O. Ghorbel, T. Frikha, A. Hajji, R. Alabdali, R. Ayadi, M.Abbas Elmasry, Blockchain-based supply chain system for olive fields using WSNs, Comput. Intell. Neurosci. 2022 (2022) 9776776.
[177] J. Ktari, T. Frikha, F. Chaabane, M. Hamdi, H. Hamam, Agricultural lightweight embedded blockchain system: a case study in olive oil, Electronics. (Basel) (2022).
[178] A. Tang, E.T. Tchao, A.S. Agbemenu, E. Keelson, G.S. Klogo, J.J. Kponyo, Assessing blockchain and IoT technologies for agricultural food supply chains in Africa: a feasibility analysis, Heliyon. 10 (15) (2024) e34584.
[179] C. Palocci, K. Presser, A. Kabza, E. Pucci, C. Zoani, A search engine concept to improve food traceability and transparency: preliminary results, Foods. (2022).
[180] S. Violino, F. Pallottino, G. Sperandio, S. Figorilli, L. Ortenzi, F. Tocci, S. Vasta, G. Imperi, C. Costa, A full technological traceability system for extra Virgin olive oil, Foods. (2020).
[181] M. Conti, EVO-NFC: extra Virgin olive oil traceability using NFC suitable for small-medium farms, IEEe Access. 10 (2022) 20345–20356.
[182] S.E. Chatziantoniou, D.J. Triantafillou, P.D. Karayannakidis, E. Diamantopoulos, Traceability monitoring of Greek extra virgin olive oil by Differential Scanning Calorimetry, Thermochim. Acta 576 (2014) 9–17.
[183] E.P. Kechagias, S.P. Gayialis, G.A. Papadopoulos, G. Papoutsis, An ethereum-based distributed application for enhancing food supply chain traceability, Foods. (2023).
[184] R. Guido, G. Mirabelli, E. Palermo, V. Solina, A framework for food traceability: case study–Italian extra-virgin olive oil supply chain, International Journal of Industrial Engineering and Management 11 (1) (2020) 50–60.
[185] G. Messina, G. Modica, The role of remote sensing in olive growing farm management: a research outlook from 2000 to the present in the framework of precision agriculture applications, Remote Sens. (Basel) 14 (23) (2022).
[186] G. Messina, G. Modica, Twenty years of remote sensing applications targeting landscape analysis and environmental issues in Olive growing: a review, Remote Sens. (Basel) 14 (21) (2022).
[187] A. Carella, P.T. Bulacio Fischer, R. Massenti, R.Lo Bianco, Continuous plant-based and remote sensing for determination of fruit tree water status, Horticulturae 10 (5) (2024).
[188] L.J. Velazquez-Chavez, A. Daccache, A.Z. Mohamed, M. Centritto, Plant-based and remote sensing for water status monitoring of orchard crops: systematic review and meta-analysis, Agric. Water. Manage 303 (2024).
[189] N. Crespo, L. Padua, J.A. Santos, H. Fraga, Satellite remote sensing tools for drought assessment in vineyards and olive orchards: a systematic review, Remote Sens. (Basel) 16 (11) (2024).
[190] K.U. Majikumna, M. Zineddine, A.E.H. Alaoui, Olive tree drought stress: a systematic review, J. Water. Clim. Chang. 15 (12) (2024) 5741–5762.
[191] C. Parra-López, S. Ben Abdallah, G. Garcia-Garcia, A. Hassoun, H. Trollman, S. Jagtap, S. Gupta, A. Aït-Kaddour, S. Makmuang, C. Carmona-Torres, Digital technologies for water use and management in agriculture: recent applications and future outlook, Agric. Water. Manage 309 (2025) 109347.
[192] N.T. Anderson, K.B. Walsh, D. Wulfsohn, Technologies for forecasting tree fruit load and harvest timing-from ground, sky and time, Agronomy-Basel 11 (7) (2021).
[193] Y. Lebrini, A.A. Gotor, Crops disease detection, from leaves to field: what we can expect from artificial intelligence, Agronomy-Basel 14 (11) (2024).
[194] L. De La Fuente, J.A. Navas-Cortes, B.B. Landa, Ten challenges to understanding and managing the insect-transmitted, Xylem-limited bacterial pathogen xylella fastidiosa, Phytopathology. 114 (5) (2024) 869–884.
[195] L. Grandi, M. Oehl, T. Lombardi, V.R. de Michele, N. Schmitt, D. Verweire, D. Balmer, Innovations towards sustainable olive crop management: a new dawn by precision agriculture including endo-therapy, Front. Plant Sci. 14 (2023).
[196] M.A. Broussard, M. Coates, P. Martinsen, Artificial Pollination Technologies: a review, Agronomy-Basel 13 (5) (2023).
[197] A. Scalisi, M.G. O'Connell, D. Stefanelli, S. Zhou, T. Pitt, D. Graetz, K. Dodds, L. Han, R. De Bei, J. Stanley, K. Breen, I. Goodwin, Narrow orchard systems for pome and stone fruit-a review, Sci. Hortic. 338 (2024).
[198] A. Caratti, S. Squara, C. Bicchi, E. Liberto, M. Vincenti, S.E. Reichenbach, Q. Tao, D. Geschwender, E. Alladio, C. Cordero, Boosting comprehensive two-

dimensional chromatography with artificial intelligence: application to food-omics, Trac-Trends in Analytical Chemistry 174 (2024).
[199] C.-z. Wu, Y.-t. Wang, D. Hu, T. Sun, Research progress of near-infrared spectroscopy in the detection of edible oil adulteration, Spectroscopy and Spectral Analysis 43 (3) (2023) 685–691.
[200] C. Sainz-Urruela, S. Vera-Lopez, M. Paz San Andres, A.M. Diez-Pascual, Graphene-based sensors for the detection of bioactive compounds: a review, Int. J. Mol. Sci. 22 (7) (2021).
[201] E. Poeta, A. Liboa, S. Mistrali, E. Nunez-Carmona, V. Sberveglieri, Nanotechnology and E-sensing for food chain quality and safety, Sensors 23 (20) (2023).
[202] P.C. Moura, V. Vassilenko, Contemporary ion mobility spectrometry applications and future trends towards environmental, health and food research: a review, Int. J. Mass Spectrom. 486 (2023).
[203] V. Maritano, P. Barge, A. Biglia, L. Comba, D.R. Aimonino, C. Tortia, P. Gay, Anticounterfeiting and fraud mitigation solutions for high-value food products, J. Food Prot. 87 (4) (2024).
[204] A. Lanubile, L. Stagnati, A. Marocco, M. Busconi, DNA-based techniques to check quality and authenticity of food, feed and medicinal products of plant origin: a review, Trends. Food Sci. Technol. 149 (2024).
[205] L.O. Rodriguez-Manay, I. Guaita-Pradas, I. Marques-Perez, Circular economy agriculture and supply chain: a literature review, Cuadernos De Gestion (2025).
[206] A. Mir-Cerda, O. Nunez, M. Granados, S. Sentellas, J. Saurina, An overview of the extraction and characterization of bioactive phenolic compounds from agri-food waste within the framework of circular bioeconomy, Trac-Trends in Analytical Chemistry 161 (2023).
[207] M. Gottardo, D. Bolzonella, G.A. Tuci, F. Valentino, M. Majone, P. Pavan, F. Battista, Producing volatile fatty acids and polyhydroxyalkanoates from foods by-products and waste: a review, Bioresour. Technol. 361 (2022).
[208] A.M. Mohamed, B.A. Tayeh, Y.I.A. Aisheh, M.N.A. Salih, Utilising olive-stone biomass ash and examining its effect on green concrete: a review paper, Journal of Materials Research and Technology-Jmr&T 24 (2023) 7091–7107.
[209] S. Roy, T. Sarkar, V.J. Upadhye, R. Chakraborty, Comprehensive review on fruit seeds: nutritional, phytochemical, nanotechnology, toxicity, food biochemistry, and biotechnology perspective, Appl. Biochem. Biotechnol. 196 (7) (2024) 4472–4643.
[210] I.S. Afonso, B. Cardoso, G. Nobrega, G. Minas, J.E. Ribeiro, R.A. Lima, Green synthesis of nanoparticles from olive oil waste for environmental and health applications: a review, J. Environ. Chem. Eng. 12 (5) (2024).
[211] S. Losada-Barreiro, Z. Sezgin-Bayindir, F. Paiva-Martins, C. Bravo-Diaz, Biochemistry of antioxidants: mechanisms and pharmaceutical applications, Biomedicines. 10 (12) (2022).
[212] A.A. Vilas-Boas, M. Pintado, A.L.S. Oliveira, Natural bioactive compounds from food waste: toxicity and safety concerns, Foods. 10 (7) (2021).
[213] L. Li, Y. Deng, X. Meng, H. Chang, C. Ling, D. Li, Q. Wang, T. Lu, Y. Yang, G. Song, Y. Hu, Genotoxicity evaluation of silica nanoparticles in murine: a systematic review and meta-analysis, Toxicol. Mech. Methods 32 (1) (2022) 1–17.
[214] G.S. Hundal, C.M. Laux, D. Buckmaster, M.J. Sutton, M. Langemeier, Exploring barriers to the adoption of Internet of things-based precision agriculture practices, Agriculture (2023).
[215] M.-A. Jouanjean, F. Casalini, L. Wiseman, E. Gray, Issues Around Data Governance in the Digital Transformation of agriculture: The farmers' perspective, OECD Food, Agriculture and Fisheries Papers, No. 146, OECD Publishing, Paris, 2020, https://doi.org/10.1787/53ecf2ab-en.
[216] L. Reina-Usuga, C. Parra-López, C. Carmona-Torres, Knowledge transfer on digital transformation: an analysis of the olive landscape in Andalusia, Spain, Land. (Basel) 11 (1) (2022).