

Advances in cultivation, production technologies, and sustainable management of Olive (*Olea europaea* L.): A review

Alhassan Alhassan Bala*

Department of Food Science and Technology, Faculty of Agriculture, Bayero University Kano, Nigeria

*Corresponding author's email: Alhassanbalaalhassan0@gmail.com

Abstract

Olive (*Olea europaea* L.) is an economically, nutritionally, and culturally important perennial crop cultivated extensively throughout Mediterranean and other regions. However, olive production is increasingly constrained by climate change, emerging pests and diseases, water scarcity, and the need to reduce environmental contamination associated with conventional crop protection practices. Recent advances in precision agriculture, plant protection technologies, remote sensing, molecular diagnostics, and endotherapy have created new opportunities for improving the sustainability and efficiency of olive production. This review synthesizes recent developments in olive cultivation and sustainable management, with particular emphasis on innovative approaches for the detection, prevention, and control of major pests and diseases. Trunk injection and endotherapy are examined as targeted delivery approaches that can improve the uptake and distribution of plant protection materials while potentially reducing off-target losses. Advances in nano-enabled and controlled-release formulations further provide opportunities for improving the efficacy, persistence, and targetability of crop protection products. The review also highlights the

increasing application of unmanned aerial vehicles, multispectral and remote sensing technologies, machine learning, and digital phenotyping for early detection of plant stress, disease symptoms, weeds, and pest infestations and for site-specific management. Particular attention is given to major threats such as *Xylella fastidiosa*, *Verticillium dahliae*, olive leaf spot, olive knot, and important insect pests, together with the influence of climate change on their distribution and epidemiology. Integration of plant health monitoring, molecular tools, biological approaches, precision application technologies, and sustainable orchard management can contribute to more efficient and environmentally responsible olive production. Future research should focus on validating these technologies under diverse field conditions, improving delivery efficiency and diagnostic accuracy, integrating multiple data sources, and developing economically feasible management systems. Such integrated approaches can strengthen olive production resilience while supporting environmental sustainability, resource-use efficiency, and long-term productivity. © 2026 The Author(s)

Keywords: Climate change, Olive cultivation, Pest management, Precision agriculture, Sustainable production, Trunk injection

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Introduction

Olive (*Olea europaea* L.) is one of the oldest and most economically important fruit crops in the world, particularly in countries with Mediterranean climatic conditions for thousands of years (Trichopoulou, 2022). Archaeological evidence indicates that olive resources were utilized by early human populations more than 100,000 years ago, while organized olive cultivation dates back approximately 7,000 years, highlighting its long-standing importance in human history (Marquer et al., 2022; Langgut & Garfinkel, 2022). It plays a significant role in global agriculture due to its nutritional, medicinal, environmental, and economic value. In recent decades, olive cultivation has expanded beyond its traditional Mediterranean belt to several non-traditional olive-growing regions owing to increasing consumer demand for olive

oil, growing awareness of its health benefits, technological advancements, and government initiatives promoting crop diversification. Besides the Mediterranean countries, commercial olive production has gradually expanded into regions of Asia, North America, the Middle East, and Africa, demonstrating the adaptability and growing global importance of the crop. Spain remains the world's leading producer and consumer of olives, while other Mediterranean countries continue to dominate global olive production and trade (Khanum et al., 2020). The existence of extensive genetic diversity is another important characteristic of olive cultivation worldwide. Thousands of olive varieties have been identified across different ecological regions, reflecting centuries of natural adaptation and human selection. However, only a relatively small proportion of these varieties possess the agronomic characteristics, fruit quality, and oil content required for commercial cultivation. The conservation,

characterization, and accurate identification of olive germplasm remain essential for breeding programs, varietal improvement, and the selection of cultivars best suited to different environmental conditions. Nevertheless, distinguishing among closely related olive cultivars remains challenging because of considerable morphological similarity and genetic variability, emphasizing the need for reliable characterization techniques (Ghanbari et al., 2012).

In recent years, scientific interest in olive research has expanded considerably due to advances in genomics, metabolomics, and biotechnology. High-quality genome sequencing has improved the understanding of genetic diversity and stress tolerance mechanisms, whereas metabolomic studies have facilitated the identification of bioactive compounds responsible for the nutritional and pharmaceutical properties of olive products (Difonzo et al., 2022; Wang et al., 2022). These developments have stimulated research on the antimicrobial, antioxidant, and therapeutic potential of olive-derived compounds, leading to the development of specialized databases such as OliveNet™ for the characterization of olive phytochemicals and their biological functions (Di Pietro et al., 2022; Pitsillou et al., 2022; OliveNet™, 2023). Despite its global importance, olive cultivation is increasingly challenged by climate change, emerging pests and diseases, declining soil fertility, water scarcity, and the growing demand for environmentally sustainable production systems. Furthermore, international sustainability initiatives, including the European Green Deal and the United Nations Sustainable Development Goals, have encouraged the adoption of innovative and eco-friendly management practices that minimize environmental impacts while maintaining productivity and product quality (Cava Jimenez et al., 2022; Lombardo et al., 2022). Consequently, sustainable cultivation practices, precision orchard management, integrated crop protection, and resource-efficient production technologies have become essential for improving the resilience and long-term sustainability of olive production. This review provides a comprehensive overview of olive cultivation, production technologies, and sustainable management strategies that can enhance orchard productivity while supporting environmentally responsible olive production.

Olive oil is considered one of the highest-value agricultural products because of its nutritional composition, sensory characteristics, and health benefits. It is extracted directly from olive fruits through mechanical processing methods that preserve its natural chemical constituents and bioactive compounds. Depending on production methods and quality parameters, olive oil is classified into different commercial grades. Among these, extra virgin olive oil represents the highest quality category, obtained exclusively through mechanical extraction without chemical treatment and characterized by very low acidity. This premium-grade oil retains natural

antioxidants, vitamins, and beneficial fatty acids, making it highly valued in both domestic and international markets. Consequently, maintaining high production standards and appropriate post-harvest processing practices is essential for ensuring superior oil quality and market competitiveness (Hadj-Taieb et al., 2012).

The successful cultivation of olives largely depends on the adoption of scientifically recommended production technologies. Adoption of agricultural innovations is influenced by several socio-economic and institutional factors, including farmers' educational level, farming experience, access to extension services, and availability of technical information. Farmers possessing higher educational attainment and greater farming experience are generally more receptive to improved technologies because they are better able to understand technical recommendations and evaluate their potential benefits. Similarly, regular interaction with extension personnel facilitates the dissemination of modern production practices, enabling farmers to make informed management decisions. Conversely, inadequate technical knowledge, limited access to reliable information, and weak extension support remain major barriers to the adoption of improved olive production technologies in many developing countries (Ghosh et al., 2023). Human resource development also plays a fundamental role in enhancing agricultural productivity. Training programs improve farmers' technical knowledge, practical skills, decision-making capacity, and confidence in implementing modern agricultural practices (Williams et al., 2013). Effective training enables growers to understand the principles of orchard establishment, nutrient management, irrigation scheduling, pest and disease management, pruning techniques, harvesting methods, and post-harvest handling (Srivastava et al., 2012). Continuous capacity-building initiatives therefore contribute significantly to increasing productivity, improving product quality, and promoting sustainable orchard management (Sajeev & Singha, 2010; Shibu & George, 2013).

Efficient water management has become one of the most critical components of modern olive production systems. Although olive trees are naturally drought tolerant, supplemental irrigation substantially improves tree growth, flowering, fruit set, fruit size, oil yield, and overall orchard productivity, particularly under water-limited conditions. Historically, irrigation was applied only in extremely arid environments, while available water resources were preferentially allocated to more water-demanding crops. However, the introduction and widespread adoption of drip irrigation technology revolutionized olive cultivation by enabling precise and efficient water application, particularly in orchards established on uneven and sloping terrains. Modern irrigation systems have therefore become an integral component of sustainable olive production in many countries (Fernández et al., 2013). Integrated pest management is another essential aspect of sustainable olive cultivation. Insect pests significantly reduce fruit yield and quality, thereby affecting growers' profitability and market competitiveness.

Effective pest monitoring, timely detection, and appropriate management interventions are necessary to minimize crop losses and ensure sustainable production. Among the various insect pests, the olive fruit fly is recognized as one of the most destructive pests in olive-growing regions, causing severe damage to develop fruits and substantially reducing both fruit quality and oil content if left unmanaged. Consequently, regular surveillance and integrated pest management strategies are considered indispensable components of modern olive production systems (Ramezani et al., 2015).

Emerging insect pests of olive trees

The sustainability of olive cultivation is increasingly threatened by the emergence and spread of insect pests, particularly in Mediterranean regions where climate change has intensified drought, heat stress, and environmental variability. These changing climatic conditions have altered pest population dynamics, geographical distribution, and infestation patterns, increasing the vulnerability of olive orchards to severe pest outbreaks. Consequently, emerging insect pests have become a major challenge for maintaining olive productivity and fruit quality under sustainable production systems (Caselli & Petacchi, 2021). Among the most economically important pests, the olive fruit fly (*Bactrocera oleae*) remains the primary threat to olive production worldwide. The larvae feed on olive fruits, causing direct yield losses and deterioration of oil quality. Climate-driven changes in temperature, rainfall, and the activity of natural enemies have further complicated the prediction and management of *B. oleae* populations, highlighting the need for integrated pest monitoring and forecasting systems (Caselli & Petacchi, 2021). Several other insect species have recently gained importance due to their increasing incidence in olive-growing regions. The olive moth (*Prays oleae*) continues to cause significant damage to flowers, fruits, and leaves, particularly in areas experiencing pronounced climatic fluctuations (Ait Mansour et al., 2017). Likewise, the quince moth (*Euzophera bigella*) and the jasmine moth (*Palpita vitrealis*) have expanded their distribution and are becoming important pests, especially in intensive and high-density olive orchards where young trees are more susceptible to infestation (Chaouche et al., 2019).

The olive leaf gall midge (*Dasineura oleae*) has also emerged as an important pest in recent years. Larval feeding induces gall formation on leaves, disrupting normal physiological processes, reducing photosynthetic efficiency, and, under severe infestations, causing premature defoliation and yield losses. Although biological control through parasitoids shows promising potential, the economic significance of this pest is expected to increase as climatic conditions become more favorable for its development (Tondini & Petacchi, 2019; Magagnoli et al.,

2022). In addition to these emerging pests, established insect species such as the black scale (*Saissetia oleae*) continue to cause substantial economic losses by inducing stunted growth, branch dieback, defoliation, and reduced fruit production (Tena et al., 2007). Moreover, secondary pests, including *Otiiorhynchus cribricollis*, are becoming increasingly problematic in some olive-growing areas, particularly where orchard intensification limits the effectiveness of traditional mechanical control measures. The growing diversity and severity of insect pests, together with restrictions on conventional insecticides and increasing environmental concerns, underscore the need for sustainable pest management strategies. Future olive production will increasingly rely on integrated pest management (IPM), biological control, precision monitoring, and climate-based forecasting systems to minimize pest damage while reducing dependence on synthetic pesticides (Caselli & Petacchi, 2021).

Emerging bacterial pathogens of olive trees

Bacterial diseases have become an increasing threat to sustainable olive production, particularly in Mediterranean regions where climate change and the widespread distribution of insect vectors have accelerated the emergence and spread of important pathogens. These diseases reduce tree vigor, impair productivity, and compromise orchard longevity, posing significant economic challenges for the olive industry (Trkulja et al., 2022). Among the bacterial pathogens, *Xylella fastidiosa* is considered the most destructive threat to olive cultivation. Since its identification as the causal agent of Olive Quick Decline Syndrome (OQDS) in southern Italy in 2013, the pathogen has caused extensive damage to olive orchards across the Mediterranean basin. As a xylem-limited bacterium, *X. fastidiosa* is primarily transmitted by xylem-feeding insects, with the glassy-winged sharpshooter (*Homalodisca vitripennis*) serving as the principal vector in the Americas, while the meadow spittlebug (*Philaenus spumarius*) is the major vector in Mediterranean olive-growing regions. Rising temperatures and changing climatic conditions have facilitated the expansion and abundance of these insect vectors, increasing the risk of pathogen dissemination (Farigoule et al., 2022; Trkulja et al., 2022; Rossi & Rasplus, 2023).

The broad host range and remarkable genetic diversity of *X. fastidiosa* further complicate disease management. Recent genomic studies have revealed considerable variation in plasmid composition, virulence traits, and host adaptation among bacterial strains, indicating a high degree of genetic plasticity that enhances the pathogen's ability to survive within plant vascular tissues under challenging environmental conditions. These characteristics make effective control particularly difficult and necessitate continuous surveillance and molecular characterization of pathogen populations (Román-Écija et al., 2022; Velasco-Amo et al., 2022). Management of *X. fastidiosa* remains challenging because the bacterium colonizes the xylem, where conventional foliar bactericides have limited effectiveness. Furthermore, the

restricted availability of approved systemic antibacterial products has increased interest in alternative management approaches, including mineral-based products, nutritional treatments, antimicrobial peptides, and integrated disease management strategies. Although these alternatives have shown promise, their field performance and long-term effectiveness require further investigation before they can be widely adopted in commercial olive production (Morelli et al., 2021; Baró et al., 2022; Catalano et al., 2022). Another economically important bacterial disease of olive is olive knot, caused by *Pseudomonas savastanoi* pv. *savastanoi*. This pathogen induces characteristic tumor-like galls on stems and branches, reducing tree vigor and productivity while creating entry points for secondary infections. Despite its long history and widespread occurrence in olive-growing regions, the disease is often underestimated because early symptoms are overlooked and disease incidence is difficult to quantify accurately. Current research is focused on understanding the pathogen's virulence mechanisms, host interactions, and the role of olive-associated microbial communities in disease development. Advances in microbiome research are expected to improve knowledge of disease epidemiology and support the development of more effective and sustainable management strategies (Ramos et al., 2012; Anguita-Maeso et al., 2023; Koščak et al., 2023).

Emerging fungal pathogens of olive trees

Fungal diseases remain one of the major constraints to sustainable olive production, particularly under changing climatic conditions and the intensification of modern orchard management practices. Increased temperatures, altered rainfall patterns, high-density plantations, and expanded irrigation systems have created favorable conditions for the development and spread of several fungal pathogens, leading to significant reductions in tree vigor, yield, and fruit quality. Consequently, the emergence of new fungal diseases and the increased severity of established pathogens have become major concerns for olive growers worldwide (Montes-Osuna et al., 2020). Among the vascular fungal pathogens, *Verticillium dahliae*, the causal agent of *Verticillium wilt*, is considered one of the most destructive diseases of olive trees. As a soil-borne and xylem-colonizing fungus, it disrupts water and nutrient transport, resulting in chlorosis, wilting, branch dieback, reduced productivity, and, in severe cases, complete tree mortality. The incidence and severity of *Verticillium wilt* have increased in intensive olive production systems, particularly in orchards established on previously irrigated agricultural lands, highlighting the influence of cropping history and irrigation practices on disease development (Jiménez-Díaz et al., 2012; Montes-Osuna et al., 2020).

The effective management of *V. dahliae* remains challenging because of its long-term persistence in soil and

limited availability of effective control measures. Recent studies have demonstrated that balanced mineral nutrition, particularly adequate potassium supply, may enhance tree tolerance by reducing disease progression. Furthermore, alternative management strategies, including the application of copper phosphite, beneficial microorganisms such as *Aureobasidium pullulans* and *Bacillus amyloliquefaciens*, and targeted trunk injection techniques, have shown promising potential for improving disease suppression while reducing dependence on conventional fungicides. These approaches are increasingly being incorporated into integrated disease management programs for sustainable olive cultivation (López-Moral et al., 2022; Mulè et al., 2002). Another important fungal disease affecting olive production is olive leaf spot, caused by *Venturia oleaginea*. This pathogen is widely distributed throughout olive-growing regions and causes premature defoliation, reduced photosynthetic capacity, and significant yield losses. The increasing occurrence of fungicide resistance, together with restrictions on copper-based fungicides and the growing demand for environmentally friendly disease management strategies have intensified research into sustainable alternatives for controlling this disease (Buonaurio et al., 2023).

Advances in disease surveillance and molecular diagnostics have also facilitated the identification of several emerging fungal pathogens associated with olive decline. Species such as *Pleurostoma richardsiae*, responsible for twig and branch dieback, have recently been detected in olive orchards previously suspected of *Verticillium wilt* infection. Likewise, *Dematophora* (Rosellinia) *necatrix* and *Emmia lacerata* have been identified in young olive trees exhibiting severe wilting symptoms, indicating that the diversity of fungal pathogens affecting olive production may be greater than previously recognized. These findings emphasize the importance of continuous monitoring and accurate pathogen identification for the early detection and effective management of emerging diseases (Calvo-Peña et al., 2022; Fusco et al., 2022). The increasing incidence of fungal diseases, combined with climate change and stricter regulations on conventional fungicides, highlights the urgent need for sustainable disease management strategies. Future research should focus on integrating resistant cultivars, biological control agents, balanced nutrient management, precision disease diagnostics, and innovative delivery technologies to develop environmentally friendly and effective approaches for protecting olive orchards against emerging fungal pathogens (López-Moral et al., 2022; Buonaurio et al., 2023).

Precision orchard management using innovative application and formulation technologies

The transition toward sustainable olive production has accelerated the adoption of precision arboriculture, which emphasizes the accurate and site-specific application of crop protection products and orchard management practices (Fig. 1). Precision technologies aim to maximize the efficiency of

agricultural inputs while minimizing environmental impacts, making them increasingly important for addressing the challenges of climate change, emerging pests and diseases, and stricter environmental regulations. Although technical and regulatory challenges still limit widespread implementation, continuous advances in digital agriculture are expanding the range of precision tools available for olive cultivation (Faupel et al., 2023). One of the most promising developments in precision arboriculture is the use of unmanned aerial vehicles (UAVs) and drone-based technologies. Besides their potential for targeted pesticide application, UAVs are increasingly employed for remote sensing, multispectral imaging, and early detection of weeds, nutrient deficiencies, water stress, and disease symptoms in olive orchards. These technologies enable timely management decisions and improve resource-use efficiency while reducing unnecessary chemical applications. Studies conducted in other perennial crops have also highlighted the importance of optimizing spray equipment, nozzle design, and adjuvant selection to improve droplet deposition and spray coverage, providing valuable information for the future application of UAV-based spraying in olive orchards (Guo et al., 2022; Yao et al., 2022; Torres-Sánchez et al., 2023).

Artificial intelligence, robotics, and automated monitoring systems are also transforming modern olive production. Machine learning algorithms integrated with multisensory robotic platforms can accurately monitor tree health, map orchard variability, and support precision management of tree canopies and trunks. These innovations have the potential to improve disease detection, optimize pruning operations, and facilitate automated orchard management, thereby enhancing productivity while reducing labor requirements (da Silva et al., 2022). In addition to precision application technologies, advances in formulation science have created new opportunities for improving the efficiency of crop protection products. Controlled-release and "smart" formulations are designed to enhance the stability, persistence, and target-specific delivery of active ingredients while minimizing losses due to degradation, volatilization, or leaching. Compared with conventional formulations, these advanced delivery systems can improve systemic movement, prolong biological activity, reduce application frequency, and lower environmental contamination, thereby supporting more sustainable crop protection strategies (Kalaydina et al., 2018; Li et al., 2021). Microencapsulation and nanoformulation technologies have emerged as particularly promising approaches for olive crop protection. A variety of carrier materials, including polymers, lipids, clay minerals, metals, and nanocomposites, have been investigated for the controlled release of pesticides and bioactive compounds. These formulations improve the stability of active ingredients against ultraviolet radiation, enhance adhesion

to plant surfaces, increase rainfastness, and improve biological efficacy. Recent studies have demonstrated that encapsulated insecticides and natural products exhibit superior performance compared with conventional formulations, highlighting their potential for environmentally friendly pest management (Graily Moradi et al., 2019; Chen et al., 2020; Li et al., 2021).

Recent innovations have also focused on utilizing biodegradable agricultural residues as carriers for crop protection products. Cellulose nanocrystals derived from olive pruning residues have demonstrated antimicrobial activity against *Pseudomonas savastanoi* and may serve as sustainable nanocarriers for delivering antimicrobial compounds in olive orchards. Such approaches not only improve the effectiveness of crop protection products but also promote waste valorization and support circular bioeconomy principles within olive production systems (Schiavi et al., 2022). Precision arboriculture, combined with innovative formulation technologies, represents a promising strategy for the future of sustainable olive production. The integration of precision monitoring, UAV-based sensing, artificial intelligence, robotics, and controlled-release formulations can improve pest and disease management, optimize resource utilization, reduce pesticide inputs, and minimize environmental impacts. Continued research and technological development will further facilitate the adoption of these advanced approaches, contributing to resilient, productive, and environmentally sustainable olive production systems (Li et al., 2021; Faupel et al., 2023).

Endo-therapy in olive trees: Precision delivery through trunk injection

Endo-therapy, also known as trunk injection, is an emerging precision agriculture technology that enables the direct delivery of active ingredients into the vascular system of olive trees. Unlike conventional foliar sprays or soil drenches, trunk injections deliver compounds directly into the xylem, resulting in rapid systemic distribution, improved target specificity, reduced chemical losses, and lower environmental contamination. These advantages make endo-therapy particularly suitable for managing vascular pathogens, nutrient deficiencies, and insect pests while reducing pesticide use and water consumption (Zamora & Escobar, 2000; Berger & Laurent, 2019; Archer et al., 2022a). Several trunk injection systems have been developed for woody crops, differing in injection pressure and drilling methods. Drill-based systems generally provide faster uptake and greater distribution of injected compounds by exposing a larger xylem area, whereas drill-free systems minimize tree injury and wound responses. Likewise, high-pressure injection devices reduce treatment time and allow the administration of larger solution volumes, while low-pressure systems decrease the risk of phytotoxicity and xylem cavitation. Therefore, selecting an appropriate injection method depends on tree physiology, target pest or pathogen, and the physicochemical characteristics of the

injected compounds (Berger and Laurent, 2019; Archer et al., 2022a).

The increasing adoption of endo-therapy in arboriculture has been driven by the need for more sustainable and efficient crop protection strategies. Trunk injection has shown considerable success in controlling vascular diseases in several perennial crops, including citrus affected by Huanglongbing disease, where systemic delivery of therapeutic compounds has demonstrated greater efficacy and reduced environmental exposure compared with conventional spray applications (Blaustein et al., 2018; Archer et al., 2022b; Vincent et al., 2022). These developments provide valuable insights into the application of endotherapy in olive production. In olive cultivation, trunk injection has been investigated for both nutritional management and disease control. Early studies demonstrated that injected systemic dyes and ferrous sulfate moved efficiently through the vascular system, confirming the feasibility of this technique for correcting iron chlorosis, a common nutritional disorder in olive trees grown on calcareous and alkaline soils (Navarro et al., 1992; Fernández-Escobar et al., 1993). More recently, endo-therapy has received considerable attention as a potential strategy for managing *Xylella fastidiosa*. Injection of zinc- and copper-based micronutrient formulations, such as Dentamet®, has shown promising results by reducing biochemical markers associated with *X. fastidiosa* infection, while laboratory studies have also confirmed the antimicrobial activity of these micronutrients against the pathogen (Scortichini et al., 2021; Girelli et al., 2022). Although these findings are encouraging, additional long-term field studies are required to evaluate treatment durability, optimize application protocols, and integrate endo-therapy into comprehensive disease management programs.

Despite its considerable potential, several challenges remain before endotherapy can be widely adopted in commercial olive orchards. Efficient distribution of injected compounds depends on numerous factors, including wood anatomy, xylem architecture, tree physiological status, environmental conditions, and the physicochemical properties of active ingredients, such as water solubility, molecular weight, lipophilicity, and electrical charge. Consequently, formulations developed for conventional foliar applications are not always suitable for vascular injection and often require modification to improve solubility, stability, compatibility, and systemic movement within the tree (Wang et al., 2020; Archer et al., 2022a). Recent research has also emphasized the importance of monitoring the movement of injected compounds within olive trees to optimize treatment efficiency. The use of systemic tracer dyes has improved understanding of vascular transport patterns and active ingredient translocation, providing valuable information for refining injection techniques and enhancing the precision of endo-therapy applications (Navarro et al.,

1992; Principles and Risks of Trunk Injection for Delivery of Crop Protection Materials, 2021; Girelli et al., 2022).

Sustainable integrated pest and pathogen management in future olive orchards

The long-term sustainability of olive production depends on the development of integrated management strategies capable of addressing the increasing challenges posed by climate change, emerging pests and diseases, labor shortages, and growing environmental concerns. Traditional olive-growing systems, particularly in Mediterranean regions, are undergoing a gradual transformation toward technologically advanced and environmentally sustainable production systems. Future olive orchards are expected to integrate precision agriculture, digital technologies, biological control, and environmentally friendly crop protection practices to improve productivity while reducing ecological impacts (Fraga et al., 2020; Technology Solutions for Future Proofing Fruit Cultivation, 2021). Integrated Pest Management (IPM) has become the cornerstone of sustainable olive production by combining biological, cultural, physical, and chemical control measures into a coordinated management strategy. Rather than relying solely on chemical pesticides, modern IPM emphasizes prevention, continuous monitoring, early diagnosis, and precision interventions that minimize pesticide use while maintaining effective control of pests and pathogens. This holistic approach not only enhances crop productivity but also supports biodiversity conservation, environmental protection, and long-term orchard resilience (Technology Solutions for Future Proofing Fruit Cultivation, 2021).

The rapid advancement of digital agriculture is expected to play a central role in future olive orchard management. Automated monitoring systems equipped with sensors, artificial intelligence, and Internet of Things (IoT) technologies can continuously assess soil properties, tree health, irrigation requirements, and nutrient status. Soil mapping technologies, including galvanic sensors and site-specific soil analyses, provide valuable information on soil fertility, moisture availability, and nutrient distribution, enabling growers to optimize fertilizer and irrigation management according to orchard variability (Uribeetxebarria et al., 2018). Early detection of diseases and pests is another essential component of sustainable olive management. Advances in remote sensing, multispectral imaging, unmanned aerial vehicles (UAVs), and artificial intelligence have greatly improved the ability to identify disease symptoms before severe damage occurs. Remote sensing technologies can detect physiological changes associated with pathogen infection, water stress, nutrient deficiencies, and weed infestations, while deep learning algorithms improve the accuracy of disease diagnosis and image classification. These technologies enable rapid decision-making and timely implementation of control measures, thereby reducing crop losses and unnecessary pesticide applications (Castrignanò et al., 2020; Ksibi et al., 2022; Messina & Modica, 2022).

Climate-based forecasting models are also becoming valuable decision-support tools in olive production. Since the development and spread of many pests and pathogens are strongly influenced by temperature, humidity, and rainfall patterns, integrating weather data with predictive models allows growers to anticipate outbreaks and implement preventive management strategies. Such forecasting systems improve the timing of pesticide applications and vector control measures while enhancing the efficiency of integrated disease management programs (Fraga et al., 2020). Future integrated management programs are also expected to incorporate innovative approaches for insect vector control. Because insect vectors play a crucial role in transmitting destructive pathogens such as *Xylella fastidiosa*, sustainable vector management has become increasingly important. Habitat manipulation, including the strategic use of ground cover species that disrupt vector life cycles, represents a promising ecological alternative to conventional insecticides. In addition, precision delivery technologies such as trunk injection (endo-therapy) offer targeted application of systemic insecticides directly into the vascular tissues, substantially reducing pesticide losses, environmental contamination, and off-target effects while improving treatment efficiency (Huang et al., 2016; Cornara et al., 2020; Lago et al., 2022; Morente et al., 2022).

Remote sensing, precision application technologies, automated monitoring, biological control, climate forecasting, and smart decision-support systems are expected to function synergistically within future IPM frameworks. The integration of these technologies can enable continuous monitoring of orchard conditions, early detection and rapid identification of emerging threats, precise and timely management interventions, reduced unnecessary pesticide applications, optimized resource utilization, and enhanced sustainability and resilience of crop protection systems. Such data-driven management systems will improve productivity, reduce production costs, minimize environmental risks, and strengthen the resilience of olive production systems under changing climatic conditions (Technology Solutions for Future Proofing Fruit Cultivation, 2021; Messina & Modica, 2022). Future of olive cultivation lies in the successful integration of advanced technologies with sustainable agricultural practices. The adoption of precision agriculture, digital monitoring, innovative crop protection technologies, ecological pest management, and intelligent decision-support systems will facilitate the development of resilient, productive, and environmentally sustainable olive orchards. Continued research, technological innovation, and collaboration among scientists, growers, and industry stakeholders will be essential to achieving sustainable integrated pest and pathogen management and ensuring the long-term viability of global olive production (Fraga et al., 2020; Messina & Modica, 2022).

Sustainable management and utilization of olive biomass

Sustainable olive production extends beyond fruit and oil yield by emphasizing the efficient utilization of residues generated throughout the production chain (Morán-Alarcón et al., 2026). Olive cultivation and processing produce considerable amounts of biomass, including annual pruning residues, leaves, pomace, olive stones, and olive mill wastewater. Traditionally, many of these by-products have been disposed of through open-field burning or landfilling, practices that contribute to environmental pollution and the inefficient use of natural resources (Donner et al., 2022; Alharbi & Ghonimy, 2025). In recent years, however, increasing attention has been directed toward transforming these materials into valuable products within the framework of sustainable agriculture and circular bioeconomy. Their effective management not only minimizes waste generation but also enhances resource efficiency, reduces greenhouse gas emissions, and creates additional economic opportunities for olive growers and processing industries (Rapa & Ciano, 2022). The expansions of olive cultivation and improvements in processing capacity have substantially increased the generation of agricultural and industrial residues. Biomass is produced during orchard management operations, especially pruning, as well as during olive oil extraction, resulting in residues such as leaves, pomace, stones, and wastewater (Manzanares et al., 2017; Ali et al., 2024). The quantity and characteristics of these materials vary according to cultivar, orchard age, climatic conditions, agronomic practices, harvesting methods, and oil extraction technologies. Rather than being regarded as waste, these biomass fractions represent renewable biological resources with significant environmental and economic value (Morán-Alarcón et al., 2026).

The various components of olive biomass possess distinct physical and chemical characteristics that determine their potential applications. Pruning residues are composed primarily of cellulose, hemicellulose, and lignin, making them suitable for soil improvement, compost production, biochar manufacture, and renewable energy generation (Romero-García et al., 2014; Lo Giudice et al., 2021). Olive leaves are rich in phenolic compounds, flavonoids, and natural antioxidants, which have attracted considerable interest for pharmaceutical, nutraceutical, and food-related applications (Erbay & Icier, 2010; Baccouri et al., 2022). Olive pomace contains residual oil, fibers, carbohydrates, and valuable phytochemicals, whereas olive stones possess high lignocellulosic content and excellent energy potential due to their elevated calorific value. Comprehensive characterization of these biomass resources provides the basis for developing efficient management strategies that maximize their agricultural and industrial utilization (García Martín et al., 2020). Modern olive production systems increasingly promote the recycling and valorization of biomass to improve environmental sustainability. Pruning residues may be

shredded and incorporated into orchard soils as organic mulch, thereby improving soil structure, conserving moisture, suppressing weeds, and increasing soil organic carbon (Kavvadias & Koubouris, 2019). Composting of olive residues further contributes to nutrient recycling and enhances soil fertility. In addition, biomass can serve as a renewable feedstock for producing bioenergy, biochar, activated carbon, organic fertilizers, and other value-added products (Alharbi & Ghonimy, 2025). Olive leaves can be processed to recover high-value bioactive compounds, while pomace and stones may be utilized for renewable energy generation or converted into industrial raw materials. Such integrated management approaches reduce waste accumulation while supporting resource-efficient agricultural production (Kavvadias & Koubouris, 2019; Correa et al., 2025).

The sustainable management of olive biomass contributes significantly to the environmental, economic, and social sustainability of olive production systems. Returning organic residues to the soil improves nutrient cycling, enhances microbial activity, and increases long-term soil fertility while reducing dependence on synthetic fertilizers. Simultaneously, the conversion of surplus biomass into renewable energy and high-value products diversifies farm income and improves the profitability of olive production (Alharbi & Ghonimy, 2025). These practices support climate change mitigation through carbon sequestration, lower greenhouse gas emissions associated with waste disposal, and promote circular resource use within olive-growing regions. Consequently, integrating biomass management into modern olive cultivation systems represents an essential component of sustainable production technologies and environmentally responsible orchard management (Galán-Martín et al., 2022).

Sustainable utilization of olive biomass for renewable energy production

The sustainability of olive production can be significantly enhanced through the efficient utilization of biomass generated during orchard management and olive oil processing. Annual pruning operations, together with olive leaves, pomace, stones, and other processing residues, provide abundant lignocellulosic biomass that can be converted into renewable energy (Almoselhy & Usmani, 2025). The conversion of these residues into biofuels not only reduces environmental pollution associated with waste disposal but also contributes to energy security, greenhouse gas mitigation, and the development of circular agricultural systems (Melloni & Cardoso, 2023).

i. Production of liquid biofuels

Olive-derived lignocellulosic biomass has attracted considerable attention as a renewable feedstock for second-generation biofuel production. Pruning residues, olive

leaves, pomace, and olive stones contain appreciable amounts of cellulose and hemicellulose that can be converted into fermentable sugars through appropriate pretreatment technologies (Bušić et al., 2018). These sugars are subsequently transformed into bioethanol through enzymatic hydrolysis and microbial fermentation. Various pretreatment methods, including dilute acid hydrolysis, steam explosion, liquid hot water treatment, microwave-assisted processing, and alkaline pretreatments, have been investigated to improve biomass digestibility and enhance sugar recovery. Selection of an appropriate pretreatment method is critical because it directly influences ethanol yield, process efficiency, and environmental sustainability (Ruiz et al., 2017). Recent technological developments have focused on improving efficiency of fermentation by employing specialized microorganisms capable of utilizing both glucose and xylose released from olive biomass. Simultaneous saccharification and fermentation has also emerged as an effective strategy to reduce processing costs while improving bioethanol productivity. Despite these advances, commercial implementation remains constrained by pretreatment costs, inhibitor formation, and the need for efficient biomass fractionation technologies (Tran et al., 2020; de la Puente et al., 2026).

ii. Production of gaseous biofuels

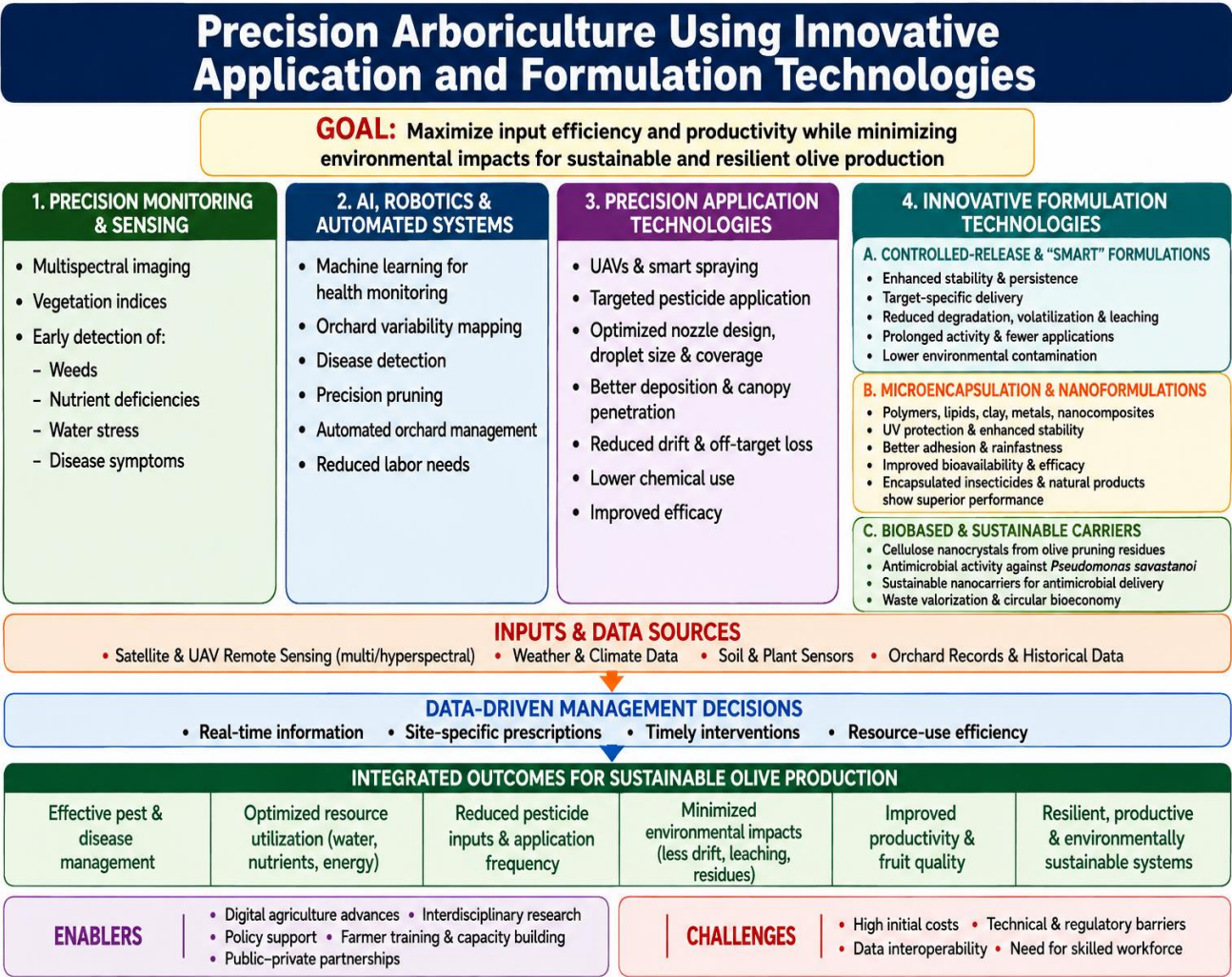
Olive biomass also represents an important renewable resource for gaseous biofuel production. Organic residues such as olive pomace, leaves, pruning biomass, and olive mill wastewater can be converted into biogas through anaerobic digestion, producing methane-rich gas suitable for heat and electricity generation (Santos et al., 2025). This biological process simultaneously reduces organic waste while generating renewable energy and nutrient-rich digestate that can be recycled as an organic fertilizer. Hydrogen production from olive biomass has also received increasing research attention because of its potential as a clean energy carrier (Enaime et al., 2024). Both biological fermentation and thermochemical conversion technologies have demonstrated the feasibility of producing hydrogen from olive-derived feedstocks. However, further improvements in conversion efficiency, process economics, and large-scale implementation are required before these technologies can become commercially viable (Sözer, 2024).

Importance for sustainable olive production

The integration of renewable energy production into olive production systems offers substantial environmental and economic benefits. Utilizing agricultural residues for biofuel generation minimizes waste accumulation, reduces dependence on fossil fuels, and lowers greenhouse gas emissions (Teksoy & Şen, 2025). Furthermore, biomass valorization creates additional income opportunities for olive growers while supporting circular resource management and enhancing the

overall sustainability of olive cultivation. Future advances in pretreatment technologies, microbial biotechnology, and integrated biomass processing are expected to improve the efficiency and economic feasibility of renewable energy

production from olive residues, thereby strengthening the sustainability of the global olive industry (Katsafadou et al., 2025).



with olive trees for water and nutrients, particularly under rainfed conditions or in regions with limited precipitation. Therefore, successful implementation requires careful selection of species and appropriate management strategies that balance ecological benefits with crop productivity (Gómez, 2017; Zipori et al., 2020). Factors such as the biological cycle of both cover crop and olive trees, climatic conditions, soil characteristics, and termination timing should be considered to minimize competition while maximizing ecosystem services (White et al., 2016).

Different botanical groups can be used as cover crops, including grasses, legumes, brassicas, and spontaneous vegetation. Among these, self-reseeding annual legumes are particularly suitable for olive orchards because they provide effective soil protection during autumn and winter while completing their life cycle before the peak water demand of olive trees (Abdalla et al., 2019). Their ability to fix atmospheric nitrogen through symbiosis with rhizobia enhances soil fertility, increases biological activity, and improves nutrient availability. The

decomposition of legume residues during spring further releases nutrients that become available during periods of active olive growth, thereby enhancing photosynthetic performance, tree nutritional status, soil moisture conservation, fruit yield, and oil production (Rodrigues et al., 2019; Martins et al., 2023). Long-term experiments have also demonstrated that permanent natural vegetation can substantially improve soil microporosity, organic carbon content, fruit production, and olive oil yield compared with conventional tillage systems (Koudahe et al., 2022). Similarly, species such as *Brachypodium distachyon* have been shown to enhance soil organic matter accumulation and nitrogen availability in intensive olive orchards. Nevertheless, further research is needed to optimize cover crop species selection, sowing and termination schedules, management under diverse climatic conditions, and economic feasibility, particularly for smallholder production systems where short-term management costs remain an important consideration (Gucci et al., 2012; Repullo-Ruibérriz de Torres et al., 2021).

Endo-therapy in Olive Trees: Precision Delivery through Trunk Injection

Concept: Direct delivery of active ingredients into the vascular system (xylem) for rapid systemic distribution, high efficacy and sustainability

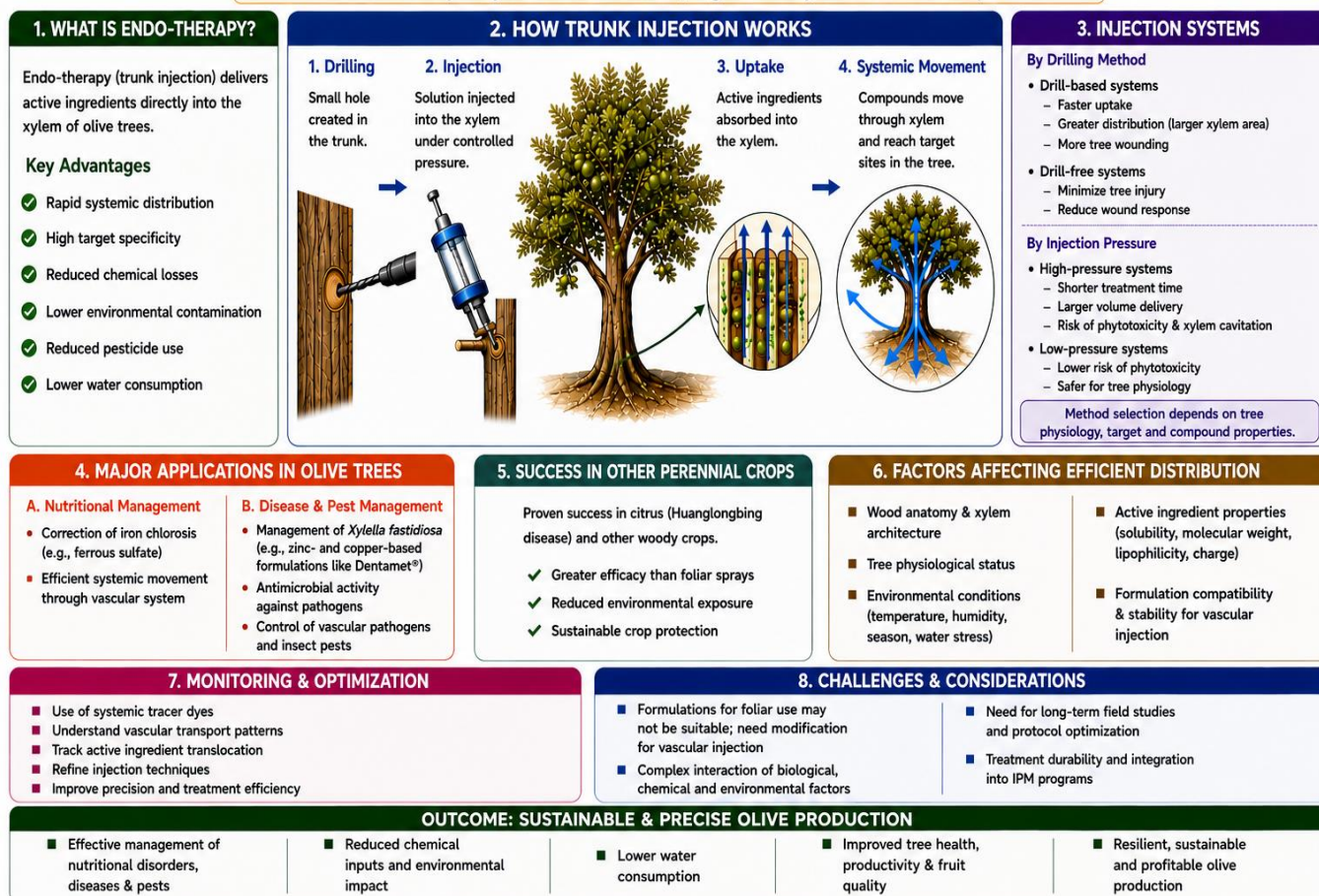


Fig. 2 Endo-therapy in olive trees through trunk injection, illustrating the injection process, systemic xylem movement, major applications, injection methods, factors affecting distribution, monitoring, challenges, and its potential for sustainable and precise olive production.

SUSTAINABLE MANAGEMENT AND UTILIZATION OF OLIVE BIOMASS

CONCEPT: Efficient management and valorization of olive by-products within a circular bioeconomy to reduce waste, enhance resource efficiency, and create economic and environmental benefits.

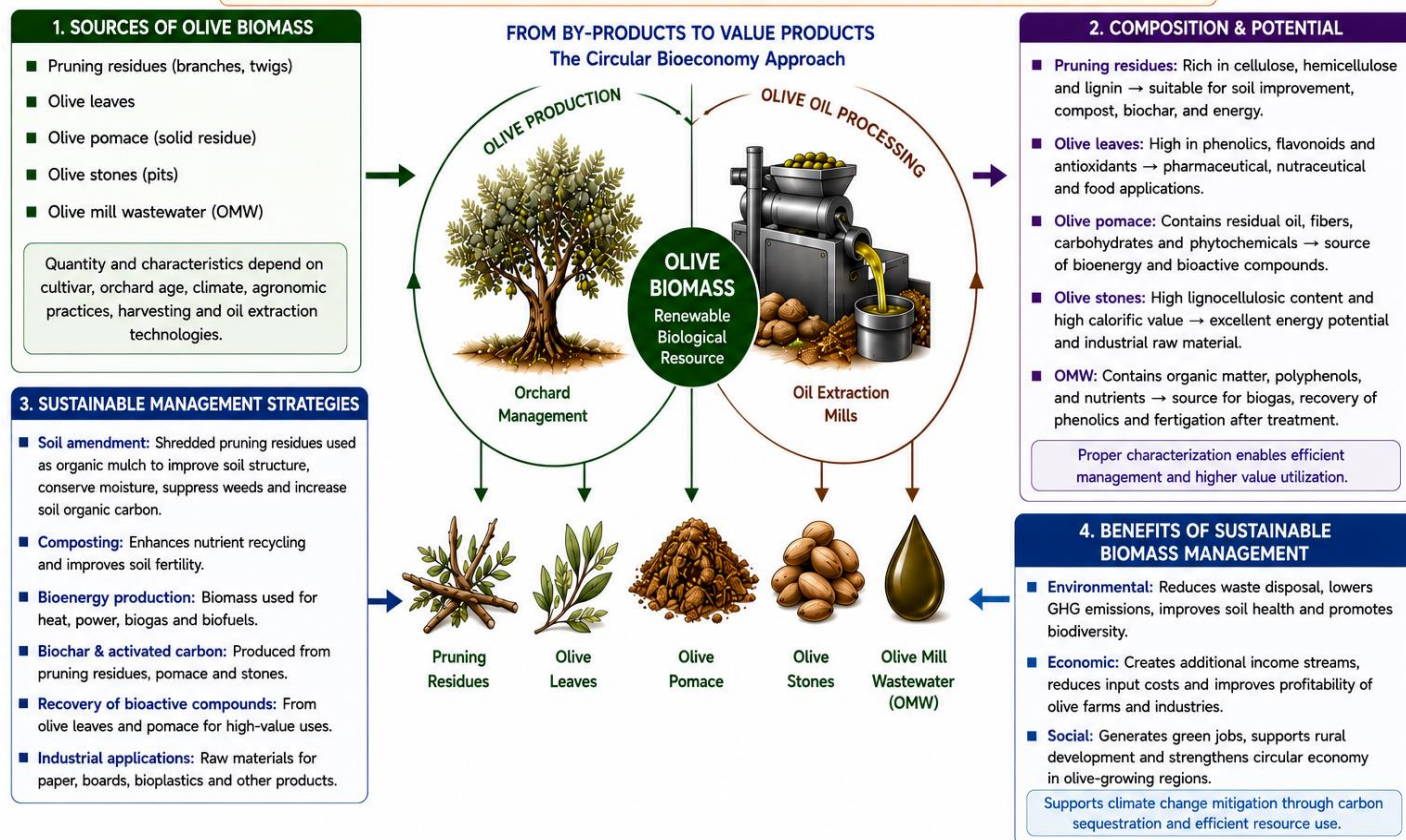


Fig. 3 Conceptual framework of sustainable management and utilization of olive biomass, illustrating major biomass sources, their composition and potential, sustainable management strategies, and environmental, economic, and social benefits within a circular bioeconomy framework.

ii. Mulching

Mulching is an important soil conservation practice in sustainable olive production that involves covering the soil surface with natural or synthetic materials to provide a permanent or semi-permanent protective layer (Jordán et al., 2010). A wide range of mulching materials, including crop residues, pruning wastes, biological geotextiles, gravel, and crushed stones, have been utilized in olive orchards depending on local resource availability and orchard management objectives (Prosdocimi et al., 2016). The adoption of mulching has increased considerably in Mediterranean olive-growing regions because it provides multiple agronomic and environmental benefits while supporting the long-term sustainability of orchard ecosystems (Mulumba & Lal, 2008). By protecting the soil surface from direct exposure to rainfall, solar radiation, and wind, mulching improves soil quality, enhances ecosystem resilience, and contributes to sustainable orchard management. One of the principal advantages of mulching

in olive orchards is its ability to conserve soil moisture by reducing evaporation from the soil surface (Jordán et al., 2010). This function is particularly valuable in Mediterranean and other semi-arid environments where olive cultivation is frequently constrained by prolonged drought periods and limited water availability (Mulumba & Lal, 2008). The mulch layer minimizes fluctuations in soil temperature and decreases evaporative water losses, thereby maintaining a more favorable soil moisture regime throughout the growing season. Improved soil water availability promotes root activity, enhances nutrient uptake, supports vegetative growth, and reduces drought-induced stress, ultimately contributing to improved fruit development and orchard productivity (Jordán et al., 2010).

Beyond water conservation, mulching substantially improves soil physical, chemical, and biological properties. Continuous application of organic mulch increases soil organic matter through gradual decomposition, leading to improved soil aggregation, greater structural stability, enhanced porosity, and increased water infiltration (Bombino et al., 2021). These improvements reduce soil compaction, promote aeration,

stimulate microbial activity, and increase nutrient cycling, thereby improving soil fertility and supporting healthy root development. Enhanced soil biological activity further accelerates organic matter decomposition and nutrient mineralization, contributing to the long-term sustainability of olive production systems (Kabato et al., 2025). Soil erosion remains one of the most serious environmental constraints affecting olive orchards established on sloping Mediterranean landscapes. Intensive rainfall events, combined with conventional soil management practices, often accelerate runoff, nutrient losses, and degradation of fertile topsoil. Mulching provides an effective protective barrier that absorbs raindrop impact, slows surface runoff, and increases water infiltration, thereby minimizing soil erosion and conserving valuable soil resources (Nastos et al., 2025). The use of pruning residues as mulch has proven particularly beneficial because it simultaneously recycles orchard biomass while reducing runoff and soil loss and increasing soil organic matter, demonstrating an efficient circular approach to sustainable olive orchard management (Repullo-Ruibérriz de Torres et al., 2025).

The recycling of organic residues generated within olive orchards represents an environmentally sustainable approach that supports circular agriculture. Olive pruning residues, leaves, and other plant materials can be retained within the orchard as mulch rather than being removed or burned (Zipori et al., 2020). Besides reducing waste disposal problems, this practice returns organic carbon and essential nutrients to the soil, enhances biological activity, and improves soil fertility over time. Consequently, recycling orchard residues as mulch contributes to resource-use efficiency while reducing environmental impacts associated with conventional waste management practices (Cherni et al., 2026). Leguminous cover crop residues have also been investigated as organic mulch because of their relatively high nitrogen content and potential contribution to soil fertility (Rodrigues et al., 2013). However, the efficiency of nitrogen transfer from decomposing legume residues to olive trees appears to be relatively limited under field conditions. Although slight increases in soil inorganic nitrogen availability have been observed following mulching with legume biomass, improvements in leaf nitrogen concentration and fruit yield have generally been inconsistent (Quintarelli et al., 2022). These findings indicate that while legume mulches contribute positively to soil conservation, careful management is required to optimize nutrient availability and avoid overestimating their fertilizer value in olive orchards (Scavo et al., 2022).

Different mulch materials may vary considerably in their effectiveness depending on climatic conditions, soil characteristics, and orchard management practices (Gholami et al., 2026). Comparative studies have demonstrated that straw mulch can substantially improve olive yield while simultaneously enhancing soil moisture conservation and reducing weed competition (Qin et al.,

2022). Such responses highlight the importance of selecting mulch materials according to local environmental conditions and production objectives rather than applying a single management strategy universally across olive-growing regions (Saputra et al., 2025; Mohammed et al., 2026). The integration of mulching with deficit irrigation has emerged as a promising strategy for improving water-use efficiency in olive production under conditions of increasing water scarcity. Organic mulches reduce soil evaporation, allowing irrigation water to remain available within the root zone for longer periods (Alhashimi et al., 2023; Fernandes-Silva et al., 2025). Research has shown that combining rice straw mulch with regulated deficit irrigation can improve vegetative growth, flowering intensity, fruit yield, and overall tree performance while reducing irrigation requirements. Likewise, the combined application of organic mulches such as animal manure and olive pomace with irrigation practices has been reported to improve tree water status, enhance soil moisture retention, and increase olive productivity (Alhashimi et al., 2023). These integrated management strategies are becoming increasingly important as climate change intensifies drought frequency and water limitations in Mediterranean olive-growing regions. Despite the substantial agronomic and environmental advantages of mulching, several knowledge gaps remain regarding its long-term application in olive orchards (Martins et al., 2024). Greater understanding is needed concerning the decomposition rates and nutrient-release patterns of different mulch materials, their long-term influence on soil biological processes, carbon sequestration, nutrient cycling, and orchard productivity. Future research should also investigate the interactions between mulching, irrigation scheduling, fertilization, and other sustainable soil management practices under diverse agroecological conditions. Furthermore, comprehensive economic evaluations are required to determine the cost-effectiveness of various mulching systems, particularly for commercial olive plantations and resource-constrained production systems. Addressing these research priorities will facilitate the wider adoption of mulching as an integral component of sustainable olive orchard management and climate-resilient production systems (Martins et al., 2024).

Soil amendments

The maintenance of soil health is a fundamental prerequisite for achieving sustainable olive production, particularly in Mediterranean and other semi-arid regions where prolonged cultivation, low organic matter content, nutrient depletion, soil erosion, and water scarcity frequently limit orchard productivity. Sustainable soil management practices increasingly emphasize the application of soil amendments as an effective strategy for restoring soil fertility, improving soil structure, and enhancing the resilience of olive production systems. Soil amendments comprise a wide range of natural and synthetic materials that are incorporated into the soil to improve its physical, chemical, and biological properties while

creating favorable conditions for plant growth and long-term orchard sustainability (Clements et al., 2019).

The primary objective of soil amendments is not merely to supply nutrients but also to improve the overall functioning of the soil ecosystem. Their application enhances soil aggregation, porosity, aeration, water infiltration, and moisture retention, thereby promoting healthier root development and improving the efficiency of water and nutrient utilization (Babla et al., 2022). Improved soil structure also minimizes compaction, facilitates root penetration, reduces surface crust formation, and enhances resistance to erosion, ultimately supporting sustainable orchard productivity under diverse environmental conditions (Shinde et al., 2019). Another important contribution of soil amendments is the improvement of soil biological activity. Increased availability of organic substrates stimulates microbial populations responsible for nutrient mineralization, organic matter decomposition, and biochemical transformations that regulate soil fertility (Ziskin et al., 2024). Enhanced microbial diversity promotes nutrient cycling, improves soil enzyme activities, and strengthens the natural resilience of orchard soils against environmental stresses. Consequently, healthier soil biological communities contribute to improved tree nutrition, greater nutrient-use efficiency, and sustained productivity in olive orchards (Yang et al., 2020).

Beyond improving soil fertility, soil amendments contribute to the remediation and restoration of degraded soils by enhancing soil–air–water relationships and improving drainage characteristics. These improvements are particularly important in olive-growing areas affected by low soil organic matter, salinity, poor aggregation, or limited water availability. Improved soil physical conditions facilitate greater infiltration of rainfall and irrigation water while reducing runoff and nutrient losses, thereby increasing the efficiency of resource utilization and promoting environmentally sustainable orchard management (Garcia et al., 2017; Rani et al., 2026). Soil amendments also play an indirect role in integrated orchard management by improving the competitiveness of olive trees against weeds and enhancing their tolerance to pests and diseases. Improved soil fertility, balanced nutrition, and vigorous root growth strengthen tree health and increase the capacity of olive plants to withstand biotic and abiotic stresses. Consequently, the application of appropriate soil amendments contributes not only to increased productivity but also to greater stability and sustainability of olive production systems (Martins et al., 2024).

Based on their origin and composition, soil amendments can be broadly categorized as organic and inorganic materials. Organic amendments are derived from plant or animal sources and contribute substantially to improving soil organic matter content and biological activity. These materials enhance soil aggregation, increase

water-holding capacity, improve infiltration, reduce compaction, and stimulate microbial processes responsible for nutrient cycling (Lin et al., 2026; Oyebiyi et al., 2026). Common organic amendments used in olive orchards include crop residues, farmyard manure, compost, biochar, olive mill wastes, sawdust, peat, coffee grounds, and other biodegradable agricultural residues. Besides supplying nutrients, these materials improve soil quality through gradual decomposition and long-term carbon sequestration, making them important components of sustainable olive production systems (Getahun et al., 2020).

In contrast, inorganic soil amendments consist of naturally occurring minerals or industrially manufactured materials applied to correct soil chemical and physical constraints. Materials such as gypsum, lime, dolomite, zeolites, pyrites, and fly ash are commonly used to regulate soil pH, improve soil structure, increase nutrient availability, and ameliorate saline or sodic soils (Zhang et al., 2025). Many inorganic amendments are rich in essential mineral elements including calcium, magnesium, potassium, and silicon, which contribute to improved soil fertility and enhanced plant growth. Their application is particularly beneficial in degraded soils where chemical imbalances restrict nutrient uptake and root development. Synthetic soil conditioners, including polymer-based materials, have also attracted attention because of their ability to improve soil moisture retention, aggregation, and water-use efficiency with relatively low application rates (Saha et al., 2025). Additionally, industrial by-products, beneficial microorganisms, soil enzymes, and biological activators are increasingly being incorporated into integrated soil management strategies to improve soil functionality and enhance the sustainability of agricultural production systems. These innovative amendments complement conventional soil management practices by improving soil resilience and increasing the efficiency of resource utilization (Liang et al., 2025). Among the various soil amendments available for olive cultivation, particular attention has recently been given to environmentally sustainable materials such as biochar, natural zeolites, and olive mill wastes. These amendments not only improve soil fertility and water-use efficiency but also promote carbon sequestration, nutrient conservation, waste recycling, and circular bioeconomy principles. Their multifunctional role in improving soil quality while reducing environmental impacts has made them promising components of sustainable olive orchard management. The following sections discuss these amendments in greater detail, highlighting their mechanisms of action, agronomic benefits, and potential contributions to the long-term sustainability of olive production systems (Martins et al., 2024).

i. Biochar

Biochar has emerged as one of the most promising organic soil amendments for improving soil quality and promoting sustainable agricultural production. It is a stable, carbon-rich material produced through the pyrolysis of biomass under

limited or no oxygen conditions. Owing to its highly porous structure, large specific surface area, diverse functional groups, and considerable chemical stability, biochar exhibits exceptional physicochemical properties that make it highly suitable for improving soil health and supporting sustainable olive production systems (Ding et al., 2017). Its heterogeneous composition enables interactions with various soil constituents, thereby influencing soil fertility, nutrient dynamics, microbial activity, and water availability. The characteristics and effectiveness of biochar largely depend on the nature of the feedstock and the pyrolysis conditions used during its production (Wang & Wang, 2019). A wide range of biomass materials, including wood chips, agricultural residues, organic wastes, poultry manure, and other plant-derived materials, can be utilized for biochar production. Likewise, variations in pyrolysis temperature, heating rate, and residence time considerably influence its physical and chemical properties, including porosity, surface chemistry, nutrient content, and adsorption capacity. Therefore, careful selection of feedstock and production technology is essential to produce biochar with properties suitable for agricultural soil amendment and long-term soil improvement (Mesquita, 2014).

Biochar contributes to soil improvement through several complementary mechanisms. Its highly porous structure enhances soil aeration, increases water infiltration, and improves water-holding capacity, thereby reducing moisture stress during periods of limited rainfall (Jones et al., 2012). The extensive pore network also provides a favorable habitat for beneficial soil microorganisms, promoting microbial diversity and biological activity that are essential for nutrient cycling and soil fertility (Rawat et al., 2019). Furthermore, the high cation exchange capacity of biochar enables the adsorption and gradual release of essential plant nutrients such as ammonium, calcium, potassium, and magnesium, thereby reducing nutrient leaching losses and improving nutrient-use efficiency. In acidic soils, biochar can also increase soil pH through the immobilization of exchangeable aluminum, creating a more favorable environment for root growth and nutrient uptake. Another important environmental benefit of biochar is its remarkable capacity for long-term carbon sequestration, as the stable carbon compounds formed during pyrolysis remain in the soil for extended periods, contributing to climate change mitigation while improving soil quality (Brassard et al., 2019).

Although research on biochar application in olive orchards remains relatively limited, available studies demonstrate considerable potential for enhancing orchard sustainability and productivity. The incorporation of biochar into olive soils has been associated with improvements in photosynthetic performance, intrinsic water-use efficiency, and electron transport activity, leading to enhanced tree physiological performance and

increased fruit yield under super-intensive production systems (Joseph et al., 2021). Improved soil water retention resulting from biochar application may also reduce irrigation requirements without compromising olive productivity, representing an important strategy for water conservation in Mediterranean environments. In addition, biochar has been shown to increase soil organic carbon content and cation exchange capacity, thereby improving soil fertility and long-term nutrient retention (Sánchez-García et al., 2016). When combined with compost, biochar may further enhance microbial activity and nutrient transformations through synergistic interactions that improve soil biological functioning. Furthermore, although biochar application has shown limited effects on olive yield in some mature rainfed orchards, improvements in fruit quality have been observed, including increased concentrations of valuable phenolic compounds that enhance the nutritional and functional quality of olive oil (Lopes et al., 2022; Martins et al., 2022).

ii. Natural zeolites

Natural zeolites are crystalline, hydrated aluminosilicate minerals that have attracted considerable attention as environmentally friendly soil amendments due to their exceptional physical and chemical properties. They are primarily formed through the natural alteration of volcanic ash by groundwater or surface water, although they may also develop under certain non-volcanic saline environments (Szerement et al., 2014). Their unique three-dimensional framework of interconnected silicon and aluminum tetrahedra creates a highly porous structure that imparts remarkable adsorption, ion-exchange, and water-retention capacities (Król, 2020). These characteristics make zeolites highly suitable for improving soil fertility, nutrient availability, and water-use efficiency in sustainable olive production systems. The highly porous structure of natural zeolites enables them to absorb and gradually release water and essential nutrients, thereby improving the physicochemical properties of agricultural soils (Salahudeen et al., 2022). Their high cation exchange capacity allows the retention and controlled release of important plant nutrients such as potassium, calcium, magnesium, and ammonium, minimizing nutrient leaching while increasing nutrient-use efficiency. In addition, the ability of zeolites to repeatedly hydrate and dehydrate helps maintain a favorable soil water balance, reduces drought stress, and improves soil moisture availability during prolonged dry periods (Sfechis et al., 2015). These properties are particularly valuable for olive orchards established in Mediterranean and other semi-arid environments where water scarcity frequently limits tree growth and productivity.

Besides improving nutrient and water management, natural zeolites contribute to soil remediation by reducing the bioavailability of heavy metals and improving soil chemical conditions. In acidic soils, zeolite increases soil pH, thereby decreasing the solubility and plant uptake of potentially toxic metals while creating a more favorable environment for root

growth and microbial activity (Eroglu et al., 2017). Consequently, zeolite application not only improves soil fertility but also enhances the environmental sustainability of olive production by mitigating soil degradation and contamination. Owing to these multifunctional properties, zeolites have been increasingly utilized in agriculture as soil conditioners and slow-release fertilizer carriers (Cataldo et al., 2021). Their incorporation into fertilization programs improves nutrient retention within the root zone, allowing fertilizers to be used more efficiently while reducing application rates and production costs. Studies in olive orchards have demonstrated that zeolite-rich soil amendments substantially improve nitrogen-use efficiency, enabling reductions in nitrogen fertilizer requirements without compromising tree nutrition (Ramesh & Reddy, 2011). Enhanced nutrient availability, particularly nitrogen and potassium, has also been reported in both soil and olive leaves, highlighting the capacity of zeolites to improve nutrient uptake and overall orchard productivity (Jha & Singh, 2016).

Recent research indicates that integrating natural zeolites with other sustainable management practices further enhances their agronomic benefits. The combined use of zeolites with legume cover crops has been shown to improve photosynthetic activity, tree nutritional status, soil moisture conservation, and olive yield compared with conventional tillage systems. Furthermore, this integrated approach enhances important soil health indicators, including the availability of nitrogen, phosphorus, and boron, cation exchange capacity, microbial activity, and overall soil biological functioning (Ramesh & Reddy, 2011). Improvements in olive fruit polyphenol concentration, olive oil quality, and other quality-related attributes have also been associated with the combined application of zeolites and cover crops, indicating their potential to simultaneously improve both productivity and product quality (Shi et al., 2009; Sharma et al., 2022). Positive responses have also been reported following the application of volcanic zeolite tuff in olive orchards, where improvements in vegetative growth, leaf water status, soil nutrient availability, and overall soil chemical properties have been observed (Perez-Caballero et al., 2008; Medoro et al., 2022). In rainfed orchards established on acidic soils, zeolites have contributed to alleviating drought stress and correcting calcium and magnesium deficiencies, thereby improving tree adaptation to adverse environmental conditions. Moreover, combining zeolites with mineral fertilizers has been shown to enhance physiological and biochemical performance during periods of climatic stress while increasing soil pH, extractable potassium, cation exchange capacity, microbial biomass, and soil enzymatic activity (Al-tabbal et al., 2020). These improvements have also translated into enhanced fatty acid composition of olive fruits and superior olive oil quality, further demonstrating the importance of zeolites as multifunctional

amendments for sustainable olive cultivation (Martins et al., 2024).

iii. Olive mill waste

The rapid expansion of olive oil production has generated substantial quantities of olive mill waste (OMWs), creating significant environmental challenges for olive-producing regions. The major by-products of olive oil extraction include olive pomace and olive mill wastewater (OMWW), which are generated during the mechanical extraction process (Regni et al., 2017). In conventional three-phase centrifugation systems, approximately 1.5 m³ of wastewater is produced per metric ton of olive oil, making OMWW one of the most problematic agro-industrial effluents because of its high acidity and elevated biological and chemical oxygen demand (Safa et al., 2017; Enaïme et al., 2024). Although two-phase extraction systems have considerably reduced wastewater generation, they produce a semi-solid residue known as two-phase olive pomace with high moisture content (Markou et al., 2010). Despite their potential phytotoxicity when improperly managed, these by-products are valuable sources of organic matter, mineral nutrients, polysaccharides, anthocyanins, and diverse phenolic compounds that can be recycled within agricultural systems (Nadour et al., 2015; Aggoun et al., 2016). Their chemical composition, however, varies according to olive cultivar, harvesting period, extraction technology, and environmental conditions (Abboud et al., 2023).

In recent years, the sustainable utilization of olive mill wastes as organic soil amendments has received increasing attention as an effective strategy for promoting circular agriculture while minimizing environmental pollution. When applied under appropriate management conditions, olive mill wastes improve soil fertility by increasing soil organic matter, enhancing nutrient availability, stimulating microbial diversity, and improving soil biological activity (Mekki et al., 2006; Mechri et al., 2007). These improvements contribute to enhanced soil structure, greater nutrient cycling, and improved water-holding capacity, thereby supporting sustainable olive production. However, excessive application or inappropriate timing may adversely affect crop establishment due to the presence of phytotoxic phenolic compounds and high organic loads (Boz et al., 2003). Therefore, careful management of application rates and timing is essential to maximize agronomic benefits while minimizing potential negative effects. Several studies have demonstrated the beneficial effects of controlled olive mill waste applications in olive orchards. Long-term application of fresh olive mill wastewater has been shown to improve soil fertility, increase organic matter accumulation, and enhance nutrient cycling, while also providing an economical source of potassium and organic nutrients (Chartzoulakis et al., 2010). Continuous application under recommended rates has improved soil physicochemical properties without negatively affecting olive oil quality, indicating that properly managed OMWW can be safely incorporated into sustainable orchard management systems.

Similarly, two-phase olive pomace has been reported to promote olive tree growth without causing long-term adverse effects on soil chemical or microbiological characteristics (Abboud et al., 2023). The combined application of olive mill waste with mineral fertilizers further improves soil quality through increased organic matter accumulation and enhanced nutrient availability. In calcareous soils, the high buffering capacity facilitates the decomposition of phytotoxic phenolic compounds, thereby reducing their potential harmful effects and improving the overall efficiency of olive mill waste utilization (Podgornik et al., 2022). Nevertheless, appropriate application rates should be maintained to ensure environmental safety and sustainable soil management.

Conclusion

Olive production is facing increasingly complex challenges arising from climate change, emerging pests and diseases, resource limitations, and the environmental concerns associated with conventional crop protection practices. This article demonstrates that sustainable olive production increasingly depends on the integration of advanced plant protection technologies with precision agriculture, improved monitoring, and environmentally responsible orchard management. In particular, trunk injection and endotherapy offer promising approaches for delivering plant protection materials directly into the vascular system of trees, potentially improving treatment efficiency while reducing unnecessary environmental exposure. Nano-enabled and controlled-release formulations may further enhance the targetability and persistence of active compounds. Recent developments in remote sensing, unmanned aerial vehicles, multispectral imaging, machine learning, and molecular diagnostics are also creating opportunities for earlier and more accurate detection of pests, diseases, weeds, and physiological stress. These technologies can support site-specific interventions and reduce unnecessary applications of crop protection products. The increasing threat posed by *Xylella fastidiosa*, *Verticillium dahliae*, olive leaf spot, olive knot, and important insect pests further emphasize the need for integrated and preventive management strategies. Climate change is likely to alter pest and pathogen distributions and may increase disease pressure, making adaptive management increasingly important.

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