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*Review*

# Use of Digital Technologies into Agroforestry Systems: A Review

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## Abstract

Agroforestry, an integrated land-use practice combining trees and woody shrubs with crop and animal farming, offers significant ecological and agricultural benefits, including enhanced biodiversity, improved soil fertility, and increased resilience to environmental pressures. Despite its advantages, agroforestry faces challenges such as high initial investments, long maturation periods for trees, land tenure issues and a high level of complexity in technical management. Digital agriculture introduces advanced technologies and sensors, which provide precise data on soil moisture, nutrient levels, and plant health, enabling more efficient resource use and better farm management. Integrating these sensing technologies into agroforestry can address key challenges, optimize irrigation and nutrient management, and enhance overall system productivity and sustainability. This review explores the interaction between agroforestry and digitalization, highlighting case studies, and discusses the potential for these technologies to support sustainable agriculture and climate change mitigation. Increased investment in research and development, along with supportive policies, is essential for advancing the adoption of these innovative practices in agroforestry.

**Keywords:** sustainable agriculture; precision agriculture; sensors; advanced sensing technologies; biodiversity; soil fertility; carbon sequestration; climate change mitigation; remote sensing; integrated farming systems

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## 1. Introduction

Agroforestry, the practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions [1], is a sustainable land-use strategy that contributes to more resilient and environmentally friendly agricultural landscapes [2]. Systems such as silvopasture, forest farming, alley cropping, and riparian buffer strips combine productivity with ecological benefits by enhancing biodiversity, conserving soil, improving nutrient dynamics and

water quality, and increasing carbon (C) sequestration [3,4]. In silvopasture and forest farming, for instance, trees offer shade and shelter, mitigating heat stress and promoting the health and productivity of both livestock and crops [5]. Their deep root systems also access water and nutrients from lower soil horizons, making them available to surface vegetation [6–8]. Similarly, alley cropping and riparian buffers help control runoff and nutrient losses, filter surface pollutants, and create habitats for wildlife [9,10]. From an economic perspective, agroforestry diversifies farm income through products such as timber, fruits, and nuts, an advantage particularly relevant in areas with limited agricultural returns [11,12]. This diversification contributes to financial stability and reduces economic vulnerability for farmers [13].

The benefits of agroforestry systems are extensively documented in the scientific literature, underscoring their abovementioned role in climate change mitigation, biodiversity conservation, and increased productivity. As illustrated in Figure 1, drawn from the literature collected using the keyword 'agroforestry' in the Scopus database (https://www.scopus.com, accessed on 31 July 2025), international research efforts reflect a growing recognition of agroforestry as a key approach in the global transition toward sustainable agriculture. In particular, the United States, India, Brazil, Indonesia, and China collectively account for 43% of the global research output on agroforestry (Figure 1A), demonstrating significant engagement from both developed and emerging economies. This trend highlights a shared acknowledgment of agroforestry's potential to address critical environmental and agricultural challenges. The increasing volume of scientific publications in the field further confirms its rising importance in modern agricultural systems (Figure 1B). Moreover, the disciplinary spread of agroforestry research (Figure 1C)—with major contributions from agricultural and biological sciences (41%), environmental science (25%), social sciences (8%), and earth and planetary sciences (6%)—emphasizes its inherently interdisciplinary nature and wide-reaching impact.

Abovementioned features and benefits are further confirmed and highlighted by the network visualization of indexed keywords in agroforestry research published over the last ten years, illustrating the interconnections between various keywords related to agroforestry (Figure 2; generated by VOSviewer 1.6.20, https://www.vosviewer.com).

Despite these known benefits and the efforts made by policymakers and researchers to support the adoption of agroforestry systems [14], this approach faces several challenges that hinder its widespread adoption [15]. For instance, the long-term nature of agroforestry investments can discourage the implementation of these systems, as trees may take years to yield returns, posing challenges for farmers reliant on short-term income [16]. Market access is also limited; timber and non-timber products often depend on niche or underdeveloped markets, typically inaccessible to smallholders. Strengthening value chains and improving market linkages is therefore essential for economic viability [17]. Moreover, inconsistent or vague policy support often favors monocultures, leaving agroforestry without adequate incentives or institutional backing [18]. In addition to these systemic barriers, farmers face practical challenges, including the inherent complexity of managing multiple plant and animal species within a single agroecosystem, high labor demands, and the need for context-specific long-term management strategies [19]. Furthermore, limited technical knowledge can hinder effective implementation; many farmers need training in species selection, planting techniques, and system maintenance to reduce the risk of failure and ensure long-term success [17,20]. In this scenario, the integration of advanced digital technologies can provide real-time data and insights that are crucial for managing the complexity of agroforestry systems and help farmers optimize resource use, monitor ecological interactions, and implement precise management practices [21].

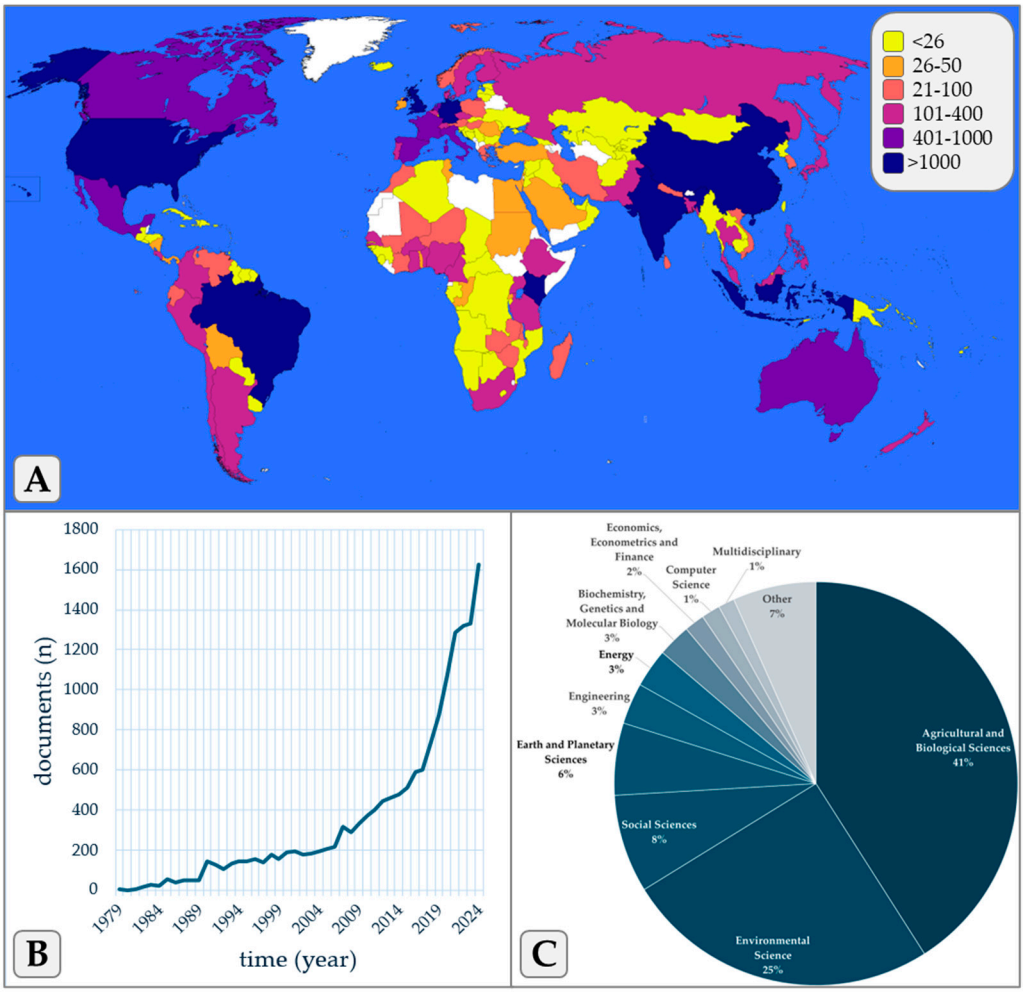


**Figure 1.** Global distribution and trends in agroforestry research. (**A**) Geographical distribution of agroforestry-related research documents produced by different countries, (**B**) temporal trend in agroforestry-related research documents published annually from 1979 to 2023, and (**C**) scientific subject area distribution of agroforestry-related research documents across various scientific disciplines. All data were obtained using 'agroforestry' as a keyword on Scopus (https://www.scopus.com, accessed on 31 July 2025).

Actually, digital agriculture, also referred to as smart farming, represents the latest phase in the evolution of agricultural practices, marked by the integration of advanced technologies such as sensors, Internet of Things (IoT), cloud computing, machine learning (ML), artificial intelligence (AI), and unmanned aerial vehicles (UAVs) to optimize productivity and sustainability (Figure 3; [22,23]). These innovations, central to the concept of digital agriculture, enable real-time monitoring and data-driven decision-making across multiple dimensions of agricultural management, including precision irrigation, fertilization, crop health monitoring, and machinery optimization [24–26]. Through the continuous collection and analysis of environmental and operational data (i.e., soil moisture, nutrient levels, weather conditions, and plant health), digital tools support more targeted, efficient, and environmentally sustainable farming practices. AI and ML, in particular, are increasingly used to analyze large datasets, predict yields, detect diseases, and improve logistics and market forecasting [27–29]. Meanwhile, the integration of IoT and cloud-based platforms facilitates remote access to real-time and historical data, while the advent of 5G enhances connectivity and responsiveness in agricultural systems [30,31]. UAVs, including drones and satellites, further enrich this technological landscape by providing high-resolution spa-

tial imagery, allowing for early detection of pests, diseases, or abiotic stress, and enabling targeted interventions [32–35].

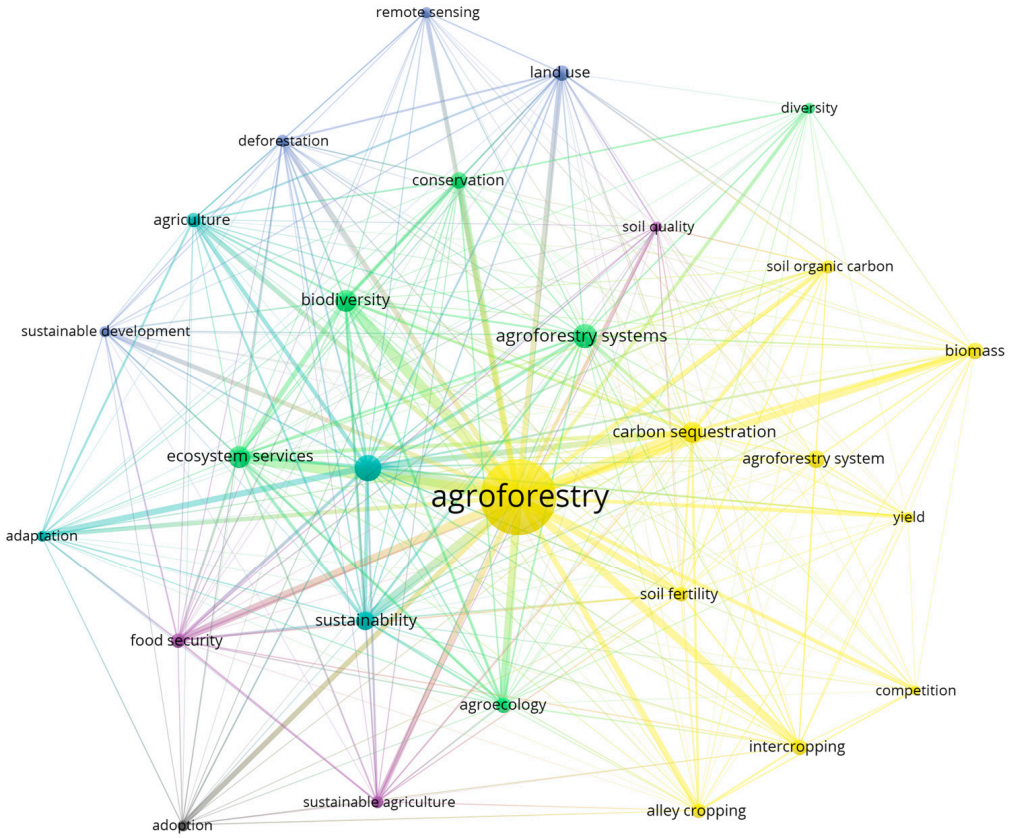


**Figure 2.** Network visualization of indexed (by authors) keywords in agroforestry research over the last ten years, illustrating the interconnections between various keywords related to agroforestry. Nodes represent keywords, with the size of each node indicating the frequency of keyword occurrence. The lines between nodes signify co-occurrences of keywords in research publications, with line thickness reflecting the strength of the relationship. Only keywords that appeared at least 100 times in the total number of articles retrieved from Scopus were selected for this analysis. This figure is generated using VOSviewer 1.6.20 (https://www.vosviewer.com/).

While digital technologies are well established in conventional agriculture, their application in complex and diversified systems such as agroforestry remains limited and underexplored, as reflected in the only and marginal presence just of the keyword "remote sensing" in related literature and research networks (Figure 2). This underutilization represents a significant knowledge gap and may hinder the wider implementation of agroforestry practices, which are crucial for fostering sustainable and resilient agricultural landscapes. Currently, the structural and functional diversity of agroforestry presents both unique challenges and promising opportunities for innovation [36]. Advanced sensing technologies can offer real-time insights that support informed decision-making, enabling precise irrigation and fertilization tailored to the specific needs of trees, crops, and livestock. These tools have the potential to enhance productivity, sustainability, and resource-use efficiency, while facilitating management and improving system resilience, especially in areas affected by water-scarcity soil degradation. Targeted research and the demonstration of practical outcomes are therefore essential to validate these technologies and promote their integration across diverse agroforestry systems.

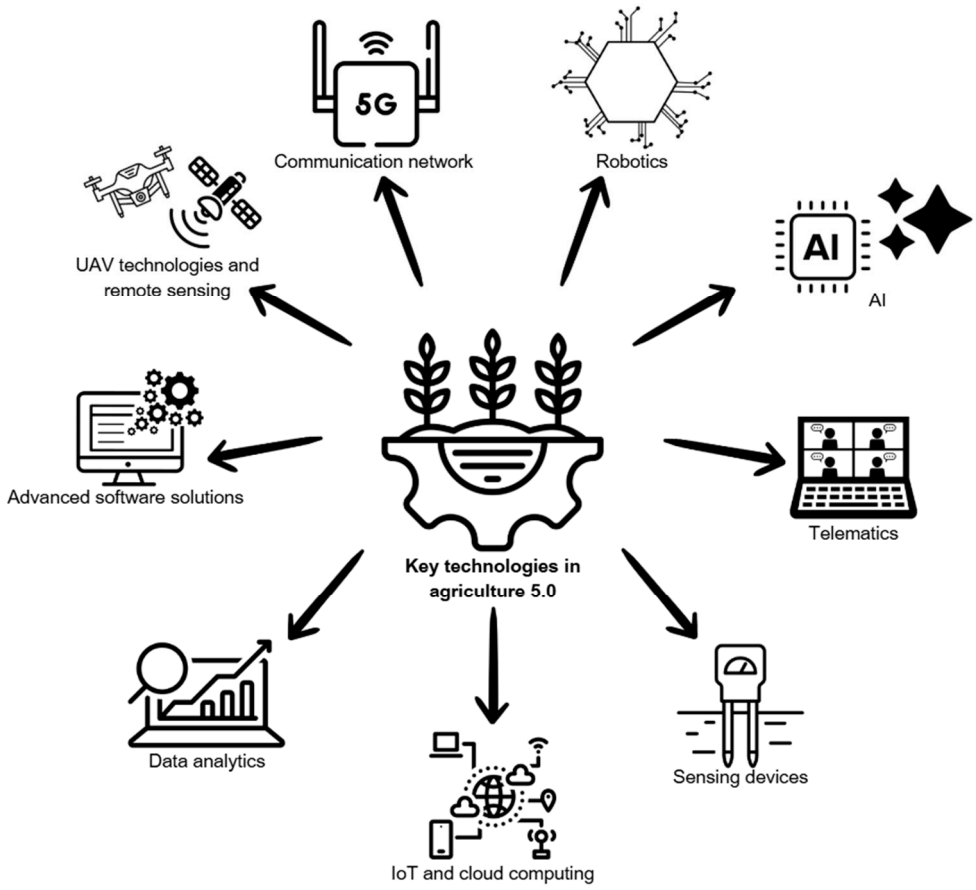


**Figure 3.** Key technologies in digital agriculture. Abbreviations: AI, artificial intelligence; IoT, internet of things; UAV, unmanned aerial vehicles.

To encourage further research in this area, this paper reviews the current state of digital agriculture in agroforestry systems. First, it reviews the literature on the use of advanced sensing technologies—including livestock, plant and soil remote sensing and advanced monitoring—within agroforestry contexts. Then, it explores case studies where digital tools have been applied in agroforestry systems, emphasizing implementation strategies, observed outcomes, and practical implications for stakeholders. Finally, a SWOT analysis is presented to identify benefits and knowledge gaps and propose perspectives for future research and innovation. The peer-reviewed literature included in this review was sourced from Web of Science (Thompson-ISI, Philadelphia, PA, USA) and Scopus (Elsevier, Amsterdam, Netherlands) databases, using multiple combinations of "agroforestry", "digital agriculture", "remote sensing" and "sensors" keywords. Database research was conducted in December 2024, covering publications from 1990 onward. In order to identify other suitable references, the reference lists of articles recorded by this literature search were examined.

## 2. The Use of Digital Technologies in Agroforestry

In the scenario of digital agriculture, the integration of advanced sensors has paved the way for groundbreaking approaches to enhance productivity, efficiency, and sustainability in agroforestry systems. Among these technological innovations, precision agriculture (PA) and precision livestock farming (PLF) have emerged as transformative paradigms, equipping farmers with tools to make data-driven decisions and optimize management practices. These approaches not only lead to improved yields, enhanced environmental performance, and increased animal welfare, but also redefine how complex, diversified

land-use systems are managed. Figure 4 illustrates this evolution, highlighting how digital technologies are being tailored to the specific characteristics of agroforestry systems. In this context, PA and PLF are not simply enhancing productivity; they are enabling a systemic transition toward adaptive and knowledge-based agroforestry management. For instance, digital tools such as virtual fencing and animal health monitoring facilitate sustainable livestock integration within forested landscapes, while plant phenotyping and stress-detection systems support targeted interventions in diverse tree–crop combinations. Similarly, soil and microclimate monitoring technologies, including soil moisture, nutrient, and greenhouse gas (GHG) sensors, provide actionable insights for maintaining soil health and mitigating environmental impacts (Table S1).

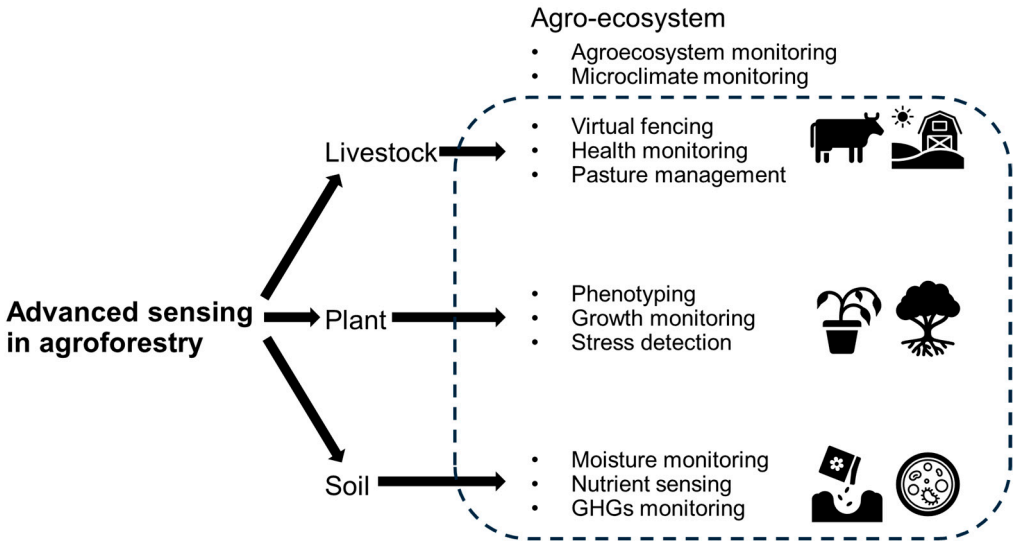


**Figure 4.** Overview of the applications of advanced sensing in agroforestry. Abbreviation: GHGs, greenhouse gases.

### *2.1. Monitoring Agroecosystem Functionality in Agroforestry Systems*

One of the primary areas benefiting from digital monitoring is the overall agroecosystem monitoring, capturing its intricate spatial and ecological diversity. Multisource satellite imagery, including data from Sentinel-2, MODIS, GEDI, and SMOS, offers a broad-scale perspective for characterizing the multiple ecosystem services provided by agroforestry systems [37]. These remotely sensed data are crucial for the accurate and effective characterization of these complex environments, enabling detailed land cover classification [38] and broad-scale aboveground biomass estimates to assess forest recovery [39]. For instance, combining Sentinel-1 (radar) and Sentinel-2 (optical) Earth Observation satellites allows for accurate mapping and discrimination of agroforestry cocoa from open canopy forest, crucial for sustainable land management [40]. Similarly, high-spatial resolution optical satellite imagery, such as that from WorldView-3, facilitates accurate species-level tree mapping and enables landscape-scale carbon accounting [41]. The integration of Landsat-5 Thematic Mapper and Sentinel 2A Multispectral Instrument data supports long-term monitoring of land use and land cover changes, vital for sustainable development and planning [42]. Beyond mere mapping, multi-temporal and multi-spectral remote sensing data can discriminate landscape characteristics linked to ecosystem and socio-cultural benefits, aiding in targeted land management interventions [43].

Understanding microclimatic conditions within agroforestry systems is another critical aspect of functionality monitoring, directly impacting crop yield, quality, and overall revenue. In situ microclimate sensors, including those for air temperature, soil moisture, soil temperature, and photosynthetically active radiation (PAR), provide detailed insights

into how trees buffer environmental conditions [44]. For example, infrared thermography effectively monitors microclimate, leading to improved agroforestry management [45], while PAR and air temperature sensors help evaluate microclimate effects on yield [46]. More comprehensive setups, featuring net radiometers, humidity sensors, and wind speed sensors, allow for the calculation of evapotranspiration and an assessment of how tree buffers influence microclimate over crops [47]. Such detailed monitoring not only enhances agroforestry resilience but also informs land use planning in freeze-prone drylands [48]. In coffee cultivation, Granier thermal dissipation sensors, microclimate sensors, soil moisture sensors, and rainfall sensors collectively assess the impact of different cultivation systems on water consumption and understand inter-species water dynamics [49].

Furthermore, digital technologies are increasingly used to monitor environmental impacts and assess the overall health of agroecosystems. Static chamber systems for in situ measurement of soil $CO_2$, nitrous oxide ($N_2O$), and methane ($CH_4$) fluxes accurately quantify greenhouse gas emissions across diverse agroforestry systems [50,51]. For land degradation and recovery assessments, tools like UAVs combined with Landsat 8 and Sentinel-2 satellite imagery support microclimate improvement and agroecosystem recovery in degraded farmland [52]. Similarly, the use of UAV-borne sensors for Digital Elevation Models, discharge sensors, and suspended sediment sensors can help reduce downstream sediment yields and support gully rehabilitation strategies [53]. These integrated monitoring approaches are essential for quantifying the benefits of agroforestry and guiding sustainable management practices.

### *2.2. Monitoring Livestock in Agroforestry Systems*

In silvopastoral systems, where trees and grazing livestock coexist, animal monitoring is essential for understanding the complex interactions among vegetation structure, microclimatic conditions, and livestock behavior. The presence of trees modifies local conditions such as shade, air temperature, and forage distribution, which influence animal movement, grazing patterns, and overall welfare. In this context, Global Positioning System (GPS) collars provide valuable data, enabling detailed analysis of spatial behavior, habitat use, and resource selection [54,55]. Such monitoring is critical for improving both productivity and animal welfare in agroforestry systems. The integration of multiple sensors, such as GPS units and accelerometers, enables comprehensive monitoring of livestock behavior and physiological responses. This multi-sensor approach allows for the detection of key behavioral states, such as resting, walking, and grazing, as well as the estimation of energy expenditure and welfare status, thereby supporting more informed management decisions [54,55]. Wearable biometric sensors measuring heart rate, body temperature, and rumination patterns have been developed to monitor physiological status in real time. These integrations facilitate early detection of heat stress, disease, or nutritional deficits, particularly important in silvopastoral systems where tree shade modifies microclimatic conditions [56]. Remote sensing technologies, such as thermal imaging cameras mounted on drones or fixed towers, can detect animal heat signatures, enabling the assessment of herd distribution and identification of individuals under stress or injury [57]. In another study, an online monitoring system was used to early detect pigs' infection through advanced biosensors and accelerometers [58].

Furthermore, another hot topic is the development of virtual fencing (i.e., the use of GPS collars and audio cues or electric shocks to control animal movement and grazing patterns) systems, to enhance grazing management in extensive livestock systems [59]. This technology allows farmers to create and adjust virtual boundaries without the need for physical fences [54], facilitating the implementation of ration stocking aiming to optimize the use of available resources, such as grass and other vegetation, while preventing both

overgrazing and overbrowsing, thereby promoting the growth of desirable biomass in both grassland and forestland. Furthermore, by setting virtual boundaries, farmers can restrict livestock access to areas that need to be conserved or regenerated, such as riparian zones, wetlands, or areas with young trees, preserving biodiversity and water quality, and preventing soil erosion [54,55].

Additionally, digital technology is also applied directly to pasture management. For instance, proximal canopy reflectance sensors are used for the estimation of key variables to aid in stocking rate adjustments [60]. Furthermore, sensors monitoring pasture variables, soil moisture, and microclimatic conditions help to better understand the belowground and aboveground competition for resources within these integrated systems [61].

### *2.3. Plant Monitoring in Agroforestry Systems*

The plant components of agroforestry systems, comprising trees, crops, and understory vegetation, demand multi-scale and multi-temporal monitoring to capture the dynamic interactions shaping system productivity and resilience [19]. Recent advancements in digital sensing technologies, coupled with the power of AI and ML, have revolutionized plant monitoring capabilities. These technologies range from remote sensing to proximal sensors, providing unprecedented insights into plant health and growth.

On the landscape scale, satellite imagery from platforms such as Sentinel-2, Landsat, and MODIS provides crucial data on vegetation cover, phenology, and biomass estimation [62]. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI) derived from these datasets enable quantification of plant vigor and photosynthetic activity, which are particularly useful for assessing tree-crop interactions and identifying zones of stress [63]. For instance, satellite imagery allows for the spatio-temporal analysis of grassland in agroforestry systems at high spatial resolution, crucial for managing forage resources [64]. Additionally, passive optical sensors (e.g., multispectral radiometers on Sentinel-2/MODIS) and active sensors (e.g., LiDAR and radar) can assess the phenological, morphological, and physiological responses of shade-adapted cultivars of winter wheat and barley, providing insights into crop performance under tree canopies [65].

UAVs equipped with multispectral, hyperspectral, and thermal cameras capture detailed information about canopy structure, leaf pigmentation, water status, and disease symptoms [66–69]. Light Detection and Ranging (LiDAR) technology is especially valuable in agroforestry, allowing the reconstruction of three-dimensional canopy architecture, tree height, and biomass distribution [65,70,71]. For example, UAV-borne RGB imagery systems are used to detect coffee plantations in tropical regions with complex agroforestry systems, aiding in mapping and management [72]. In another recent study employed UAV-borne multispectral mapping was employed to assess the impacts of stocking density and rotational grazing practices, focusing on how grazing animals influence soil health through trampling pressure, depending on whether forested areas are available for grazing or not [73]. Furthermore, UAV-borne multispectral imagery systems can map crop yield and litter, estimate tree influence distance, and compute Land Equivalent Ratio without needing sole crop data, offering a comprehensive view of system productivity [74].

Proximal sensors enable rapid, on-site assessments of plant physiological status. Chlorophyll meters and fluorescence sensors measure photosynthetic efficiency and nutrient status, while leaf temperature sensors provide indirect indicators of water stress [75,76]. For example, portable time domain reflectometry, thermal dissipation probe, and ultrasonic anemometers coupled with Campbell 2D anemometers and four temperature and humidity probes can monitor drought stress in young apple trees in a semiarid agroforestry system [77]. Soil moisture and sap flow sensors enable precise monitoring of tree water

use under drought stress, allowing for optimized irrigation strategies [78]. Dendrometers provide continuous, high-resolution measurements of stem diameter variations, serving as sensitive indicators of plant water status and growth dynamics [79]. Photosynthetic photon flux density (PPFD) sensors, air temperature sensors, leaf temperature sensors, soil temperature sensors, and relative humidity sensors assess microclimate modulation and its impact on crop ecophysiology under different tree genotypes, vital for understanding tree-crop interactions [80]. Linear quantum sensors connected to a Campbell CR1000 or CR1000X datalogger are used for monitoring light availability for pasture growth under tree canopies, crucial for silvopastoral management [60]. Heat-pulse sap flow sensors and soil-moisture probes (e.g., time domain reflectometry or capacitance sensors) can accurately, timely, and spatially estimate forest aboveground biomass [81]. These same sensors, along with sap flow sensors (i.e., heat-pulse and thermal-dissipation probes), determine the microclimate of agroforestry systems and their effects on yield and income, providing comprehensive insights into system performance [82]. Onset HOBO Data Loggers measure high-resolution, continuous micro-climate data (e.g., temperature and solar radiation) across different elevations and shade conditions within agroforestry systems [83]. Mini microclimate sensors and UAV-borne thermal images can assess spatial and temporal microclimate and land surface temperature variability, aiding in understanding the microclimatic effects of trees [84]. Wind speed sensors and uredospore traps measure how shade tree traits alter wind flow and spore dispersal, which is important for disease management in agroforestry [85]. Finally, air temperature sensors, rainfall gauges, and leaf temperature sensors capture key microclimatic factors driving coffee leaf rust development to forecast lesion emergence, sporulation, and infectious area growth, enabling proactive disease management [86].

Finally, emerging AI and ML techniques have been integrated with imaging sensors to automate pest and disease detection, a critical component of plant health management in agroforestry systems. Image recognition algorithms identify characteristic symptoms, enabling early intervention that reduces yield losses and limits pesticide use [87,88]. Beyond pest and disease detection, AI/ML models are increasingly used for yield prediction, plant phenotyping, and optimizing resource allocation based on sensor data. For example, the parameterization of agroforestry systems using AI/ML can enhance efficiency to limit spore propagation [89].

Integrating diverse plant monitoring data streams into coherent management frameworks remains a challenge. Continued development of IoT-enabled sensor networks and user-friendly decision support systems is essential to translate sensor data into actionable insights [30,87,90].

### *2.4. Soil Monitoring in Agroforestry Systems*

Soil is the bedrock of agroforestry productivity, critically influencing water availability, nutrient cycling, and biological activity [18]. Monitoring soil properties in these complex systems is challenging due to the inherent spatial heterogeneity introduced by tree roots, diverse litter inputs, and varied microclimatic conditions [18,91]. Fortunately, significant advancements in digital soil sensors and data acquisition technologies are addressing these complexities, providing sophisticated tools for precise soil management.

Accurate soil moisture assessment is paramount for efficient water use, a critical factor given the competition for resources between trees and crops in agroforestry systems. Various sensors offer continuous, non-destructive measurements of volumetric water content. Capacitive sensors, Time Domain Reflectometry, and Frequency Domain Reflectometry sensors are widely used to reveal distinct moisture regimes beneath tree canopies and in open crop alleys [92,93]. This real-time data is invaluable for optimizing irrigation schedules, conserving water, and preventing water stress, ultimately leading to improved

crop yields and enhanced sustainability [24,94]. For instance, Electrical Resistivity Tomography can map soil moisture dynamics [95], while sap flow sensors combined with micro-lysimeters enable precise assessment of water use efficiency [96]. The integration of soil moisture and sap flow sensors can also help assess the potential of silvopastoral conversion for mitigating climate change impacts and sustaining hydrological regulation [97]. By identifying areas with poor water retention or optimizing irrigation timing to match crop water requirements, these sensors significantly improve water use efficiency, particularly in water-scarce regions [35,94,98].

Nutrient availability and soil fertility are crucial for plant growth and are monitored using advanced in situ sensing technologies. Ion-selective electrodes and portable X-ray fluorescence spectrometers facilitate rapid analysis of key macro- and micronutrients directly in the field [99]. These tools support site-specific nutrient management, which optimizes fertilizer use efficiency and minimizes environmental impacts [100,101]. Recent innovations, such as optical and electrochemical sensors, including ion-selective electrodes, are revolutionizing real-time nutrient monitoring capabilities, allowing continuous, non-destructive assessment of nutrient concentrations [23,102,103]. For example, a VIS-NIR hyperspectral imager offers accurate, mobile, and cost-effective prediction of soil organic carbon and nitrogen [104]. This precision in nutrient management not only optimizes plant growth but also mitigates the risk of environmental pollution from excess nutrients [23,102,103]. Furthermore, a combination of a VNIR spectrometer, a dry combustion analyzer, and other data sources can accurately predict and map soil organic carbon [105].

Soil is a dynamic living system, playing a vital role in the global carbon cycle by storing and releasing GHGs like $CO_2$, $N_2O$, and $CH_4$. Monitoring these emissions is essential for quantifying global GHG budgets and informing land management decisions for climate change mitigation [106,107]. Advanced sensing techniques provide farmers with tools to monitor GHG emissions from their soils. Chamber systems, such as static, vented chambers, are commonly used to measure GHG fluxes from the soil surface [106,108]. These, along with sensors for soil microclimate monitoring, allow for quantification of $N_2O$ and $CO_2$ emissions, soil temperature, water content, and surface-soil inorganic nitrogen [109]. Micrometeorological methods, like eddy covariance, offer another valuable tool by measuring vertical turbulent fluxes of GHGs, providing insights into gas exchange between the soil and atmosphere [109]. Eddy covariance towers are particularly useful in extensive agroforestry systems that are clearly separated from specialized agricultural or forest stands, where edge effects may disturb flux measurements. Furthermore, the availability of lower-cost or 'mini-tower' setups now enables flux monitoring at smaller spatial scales, enhancing spatial replication and representativity [110]. Additionally, advances in biosensors allow the measurement of soil biological activity, including microbial respiration and enzymatic activity, which are critical indicators of soil health and carbon cycling [111]. Automated soil temperature sensors, combined with moisture data and weather station inputs, provide comprehensive environmental monitoring, enhancing our understanding of soil-plant-atmosphere interactions [95–97,112].

The aggregation and real-time transmission of diverse soil data have been greatly facilitated by Wireless Sensor Networks and IoT platforms, enabling adaptive management practices even in remote agroforestry areas. However, challenges persist regarding sensor calibration, data standardization, and energy management, which need to be addressed for widespread adoption [113]. Despite these challenges, the information gathered empowers farmers to make informed land management decisions that contribute to climate change mitigation and promote sustainable agroforestry practices. For instance, X-ray computed micro-tomography can evaluate soil void phase characteristics and heterogeneity of soil

matrix radiodensity, helping to characterize differences in soil surface microstructure [99]. Ultimately, comprehensive soil monitoring supports optimized resource management and enhances the resilience and environmental benefits of agroforestry systems.

## 3. Strengths, Weaknesses, Opportunities and Threats (SWOT Analysis) on the Use of Digital Technologies in Agroforestry Systems

### *3.1. Strenghts*

Advanced sensing technologies provide precise and real-time data on various environmental factors such as soil moisture, nutrient levels, pest and pathogens spread and weather conditions, enabling data-driven decision-making in agriculture [34,94]. This allows for informed decision-making, optimizing resource use, and improving overall farm management [114,115]. By utilizing sensors, farmers can automate processes like irrigation and fertilization, ensuring they are applied at the right time and in the right amount, so reducing waste and costs, and enhancing crop and livestock productivity [30,116].

In agroforestry systems, these technologies support the understanding of complex interactions between trees, crops, and livestock by enabling site-specific management and long-term monitoring of ecological dynamics [17]. Such integrated monitoring helps identify optimal spatial arrangements and management regimes, enabling site-specific decisions that maintain both productivity and ecosystem stability. Furthermore, these technologies can facilitate PA practices, allowing farmers to tailor their inputs to the specific needs of each part of their field. For example, variable-rate technology can be used to apply fertilizers or agrochemicals at different rates across the field, based on real-time sensor data on soil conditions and crop health. This not only improves efficiency but also minimizes environmental impact [117,118]. By integrating sensing technologies into agroforestry, practitioners can better manage biodiversity, soil health, and microclimatic conditions, contributing to more resilient and sustainable land-use systems [119].

### *3.2. Weaknesses*

The adoption of advanced sensing technologies, while offering significant potential, also presents several challenges. A major hurdle is that the substantial upfront investment in hardware, software, and training can be a barrier for small-scale and resource-limited farmers [13,120,121]. Implementing and maintaining these sophisticated systems often demands specialized technical knowledge and expertise, necessitating ongoing training and support. This can be time-consuming, costly, and potentially disruptive to existing farming operations [20,122].

In agroforestry systems, these challenges are further compounded by the complexity of managing multiple interacting components—trees, crops, and livestock—across heterogeneous landscapes. Furthermore, the sheer volume of data generated by these sensors presents significant challenges in terms of data storage, processing, analysis, and interpretation. Ensuring data security and privacy, especially in a connected and increasingly digitalized agricultural landscape, is paramount [123]. Over-reliance on technology can also create vulnerabilities. System failures, connectivity problems, or technical malfunctions can disrupt operations and potentially lead to significant losses [13,117,122].

Additionally, in agroforestry contexts, the risk of sidelining traditional ecological knowledge is particularly relevant, as these systems often rely on deep, site-based understanding of natural cycles and biodiversity. Excessive dependence on digital tools may inadvertently marginalize these insights, which are crucial for long-term sustainability and resilience [124].

Moreover, despite their potential, current sensing and monitoring approaches often capture only isolated parameters (e.g., soil moisture or canopy temperature) with-

out fully integrating them into system-level analyses capable of describing the dynamic interactions among trees, crops, and livestock. This limitation restricts the ability of digital tools to model the energy, water, and nutrient fluxes that drive agroforestry performance [19,74,105,110,125]. Developing interoperable data frameworks and modelling platforms able to link biophysical signals to ecosystem functions (e.g., competition, facilitation, and resource sharing) remains a key challenge for advancing digital agroforestry [30,61,64,119]. Finally, the spatial and temporal heterogeneity typical of agroforestry systems often requires high-resolution, multi-sensor integration to achieve meaningful interpretation [68,69,126]. Without this, the risk is to generate fragmented information that fails to reflect the complexity such systems are designed to harness. This highlights the need for coordinated research efforts that move beyond isolated technology testing and towards holistic frameworks for monitoring and decision support in agroforestry [9,31,92,113].

### *3.3. Opportunities*

Despite the challenges, advanced sensing technologies present numerous opportunities to revolutionize agroforestry. The field is ripe for innovation, with significant potential for developing more cost-effective, user-friendly, and integrated sensing solutions tailored to the unique needs of diverse agroforestry systems [121,127]. Growing global awareness of the urgent need for sustainable agriculture is driving increased policy support, subsidies, and funding for the adoption of these technologies [120]. Particularly promising are opportunities to use digital technologies to simulate and model biophysical processes within agroforestry systems (e.g., C sequestration, evapotranspiration, and nutrient fluxes) by integrating data from soil, plant, and atmospheric sensors. This system-level approach supports the design of management strategies that maximize facilitative interactions (e.g., shading, nitrogen fixation) while reducing resource competition. In this way, sensing technologies become not only diagnostic tools but also components of predictive and adaptive management frameworks for agroforestry. This creates a favorable environment for market expansion, enabling companies to develop innovative products and services specifically for the agroforestry sector, fostering economic growth and job creation [116,128].

Furthermore, these technologies can play a crucial role in addressing pressing global challenges such as climate change, food security, and biodiversity loss. By enabling practices, optimizing resource use, and enhancing ecosystem resilience, advanced sensing technologies can contribute significantly to the development of sustainable and resilient agroforestry systems, delivering substantial environmental, social, and economic benefits for communities worldwide [24,116,129].

To ensure inclusive and equitable access to these opportunities, it is crucial to prioritize the development of technologies that are affordable and accessible to smallholder farmers and marginalized communities [122,128,130,131].

### *3.4. Threats*

Several significant threats could hinder the widespread adoption of advanced sensing technologies in agroforestry. The high costs associated with these technologies, including hardware, software, data storage, and maintenance, can pose a significant economic barrier for many farmers, particularly in developing countries or regions with low agricultural profitability [13,121,122]. Rapid technological advancements can quickly render existing sensing systems obsolete, necessitating continuous investments in upgrades and new technologies, which can be financially burdensome and create a sense of technological obsolescence [132]. Furthermore, because agroforestry systems are inherently long-term and dynamic, technologies designed for short-term monitoring may fail to capture slow

ecological processes such as soil carbon accumulation or tree-crop competition over time. In addition, fragmented land ownership, mixed management objectives, and limited digital infrastructure in forested or rural areas further complicate its adoption. Resistance to change due to cultural, social, or psychological factors can also impede adoption, as farmers accustomed to traditional practices may be hesitant to embrace new technologies or may lack the necessary digital literacy [122,128,131].

Furthermore, the use of advanced sensing technologies raises critical ethical and regulatory concerns. Issues related to data privacy, security, and ownership of data generated by these systems require careful consideration and robust regulatory frameworks [15,36,123]. Ensuring equitable access to these technologies and their benefits, while mitigating potential risks and ensuring responsible data management, is crucial for their successful and sustainable integration into agroforestry systems.

To mitigate these threats and ensure the responsible and equitable adoption of these technologies, it is essential to prioritize the development of affordable and accessible solutions, support continuous education and training programs, and establish clear and transparent regulatory frameworks that protect farmers' rights and data privacy. Building trust between farmers, technology providers, and policymakers is crucial for addressing concerns and fostering a supportive environment for the responsible adoption of advanced sensing technologies in agroforestry (Figure 5).

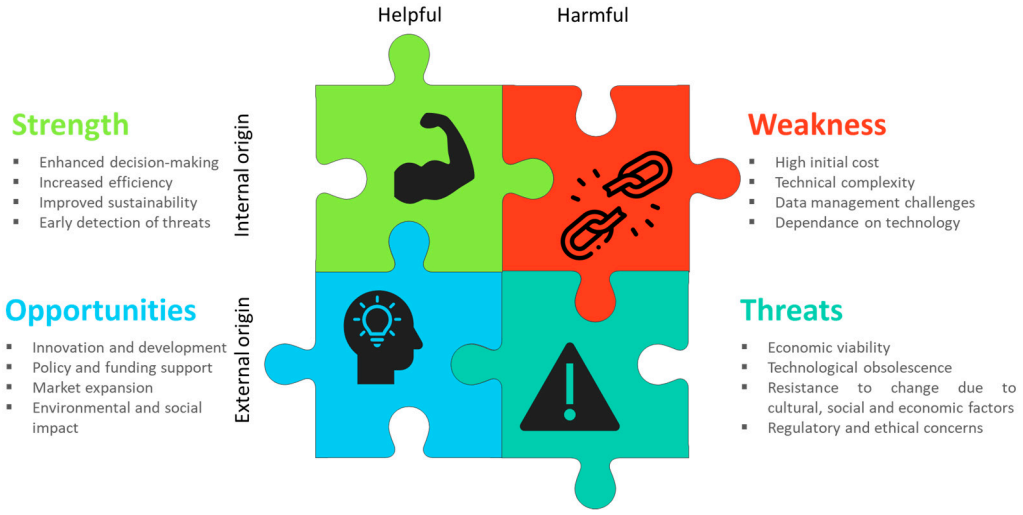


**Figure 5.** SWOT analysis summarizing strengths, weakness, opportunities and threats associated with the integration of advanced sensing in agroforestry systems.

## 4. Conclusions and Perspectives

The integration of advanced sensing technology into agroforestry systems has the potential to accelerate their adoption and improve management efficiency, productivity, and sustainability. By providing real-time data and actionable insights, sensing technologies can help farmers and advisors manage the inherent complexity of agroforestry systems, optimize resource use, and minimize trade-offs among system components.

Building on the "ecosystem–livestock–plant–soil" framework discussed in this review, future research should prioritize the development of cross-scale monitoring approaches capable of linking biophysical data (e.g., soil, plant, and microclimate dynamics) with management decisions and socioeconomic outcomes. In particular, there is a need for interoperable sensor networks and data fusion models that integrate remote, proximal, and in situ sensing to provide a holistic view of system performance.

Furthermore, targeted studies should assess the cost-effectiveness, scalability, and energy requirements of digital technologies in smallholder agroforestry contexts, where economic and infrastructural constraints often limit adoption. Strengthening collaborations among engineers, ecologists, and social scientists will be essential to co-design context-specific solutions and translate technical innovation into practical tools.

Capacity building remains important, but should now focus on developing digital literacy and participatory decision-support systems that empower farmers to interpret and apply sensor-derived information. Policy frameworks should also move beyond generic incentives to include data-sharing standards, open-access platforms, and funding schemes that foster innovation in multi-actor agroforestry networks.

By aligning technological development with the ecological and social complexity of agroforestry, future research can transform digitalization from a set of isolated tools into an integrative strategy for resilient and sustainable land-use systems.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy15122671/s1, Table S1: Overview of the applications of advanced sensing in scientific studies focused on agroforestry [37–46,48–50,52–55,58,60,61,63–65,70–72,74,77,78,80–86,89,90,95–97,99–101,104,105,109,112,126,133–152].

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