Engineering and Technology Journal e-ISSN: 2456-3358
Volume 11 Issue 09 September -2026, Page No.- 11413-11431
DOI: 10.47191/etj/v11i09.06, I.F. – 8.595

Connecting the Canopy: C-Band and Ku-Band Satellite Technologies for Sustainable Oil Palm Plantation Management in Indonesia—A Review

Loso Judijanto
IPOSS Jakarta, Indonesia, https://orcid.org/0009-0007-7766-0647

ABSTRACT: Indonesia's oil palm plantations are increasingly expected to combine high productivity with environmental protection, traceability, worker welfare, and smallholder inclusion. Achieving these objectives requires reliable digital connectivity across plantation landscapes that are frequently extensive, remote, and inadequately served by terrestrial telecommunications. This qualitative literature review examines the characteristics of C-band and Ku-band satellite technologies and critically explores their roles in supporting sustainable oil palm plantation management in Indonesia. Drawing on interdisciplinary literature published since 2020 covering satellite communications, Internet of Things, smart agriculture, remote sensing, oil palm agronomy, and sustainability governance, the review develops a socio-technical synthesis rather than a systematic or meta-analytic assessment. C-band generally provides stronger resilience to tropical rain attenuation and is attractive for fixed, availability-critical backbone connectivity, whereas Ku-band enables smaller terminals, greater deployment flexibility, and practical broadband access but requires more deliberate rain-fade mitigation. Neither band is intrinsically superior, and actual performance depends on link design, service architecture, traffic requirements, cost, and local conditions. The review identifies applications in environmental surveillance, precision agronomy, disease detection, harvesting, logistics, traceability, worker safety, and sustainability assurance. It proposes an **Observe–Connect–Decide–Act–Verify** framework and a hybrid connectivity architecture integrating field networks, satellite backhaul, terrestrial networks, edge computing, remote sensing, and analytics. Sustainable benefits ultimately depend not merely on connectivity but on inclusive governance, institutional capacity, appropriate agronomic action, and mechanisms preventing digitalization from reinforcing existing inequalities.

KEYWORDS: C-band; Ku-band; satellite communications; oil palm; sustainable plantation management; digital agriculture; Internet of Things; remote sensing; precision agriculture; Indonesia
JEL Classification : L96; O33; Q15; Q16; Q56

1. INTRODUCTION

Palm oil occupies an unusual position in contemporary debates on agricultural sustainability. Oil palm is an exceptionally land-efficient source of vegetable oil, yet plantation expansion in tropical forest and peatland landscapes has been associated with deforestation, greenhouse-gas emissions, biodiversity loss, hydrological disturbance, and social conflict. Consequently, sustainability cannot be reduced to a simple choice between expanding production and restricting cultivation. The more consequential question is how existing plantation landscapes can be managed with greater environmental accountability, higher resource-use efficiency, stronger social inclusion, and more transparent governance while avoiding displacement of environmental pressures elsewhere. Recent evidence reinforces both sides of this sustainability equation: oil palm's high productivity creates opportunities for land-efficient production, while poorly governed expansion can generate substantial ecological and social costs (Meijaard et al., 2020; Ayompe, Schaafsma and Egoh, 2021; Xu et al., 2022; Bicknell et al., 2023; Supriatna et al., 2024).

Indonesia is particularly important in this debate because its oil palm sector combines large industrial estates, plasma and partnership schemes, and a very substantial smallholder population. This heterogeneity means that sustainable plantation management involves not one technological or institutional model but multiple production environments with unequal access to capital, extension services, legal documentation, data, skilled personnel, and infrastructure. Certification studies show that independent smallholders frequently confront structural barriers involving legality, organizational capacity, finance, knowledge, land documentation, and access to institutional support. Meanwhile, sustainability certification itself produces differentiated outcomes and does not automatically guarantee equivalent welfare or environmental benefits in every locality (Apriani et al., 2020; Santika et al., 2021; Watts et al., 2021; Choiruzzad, Tyson and Varkkey, 2021; de Vos et al., 2023a; Supriatna et al., 2024).

At the same time, plantation management is entering a more data-intensive phase. Remote sensing, unmanned aerial vehicles (UAVs), geographic information systems (GIS), field sensors, artificial intelligence (AI), mobile applications, digital harvesting records, machinery telemetry, and supply-chain traceability systems are increasingly capable of improving the temporal and spatial resolution of plantation information. Contemporary smart-agriculture research demonstrates applications in crop monitoring, irrigation, agrochemical management, pest and disease detection, harvesting, logistics, and supply chains. However, the technological value chain is incomplete if data generated in the field cannot be transmitted reliably to gateways, processing systems, managers, mills, or external verification platforms (Friha et al., 2021; Tao et al., 2021; Yang et al., 2021; Qazi, Khawaja and Farooq, 2022; Shahab et al., 2024; Kumar et al., 2024; Fuentes-Peñailillo et al., 2024).

This connectivity problem is particularly relevant in oil palm landscapes. Plantations may cover extensive areas far from urban telecommunications infrastructure, while independent smallholders can be spatially fragmented across rural territories. Terrestrial cellular infrastructure is not uniformly available, fiber deployment can be economically unattractive in sparsely populated locations, and local sensor technologies such as Wi-Fi or LoRaWAN cannot themselves provide long-distance backhaul to external networks. Satellite communications therefore offer an important complementary infrastructure layer, particularly where terrestrial service is unavailable, intermittent, or unable to meet application-level reliability requirements. Evidence on the digital divide in farming and on rural multi-connectivity further indicates that access, coverage, throughput, and affordability vary substantially across farm types and locations (Rinaldi et al., 2020; Centenaro et al., 2021; Evans et al., 2021; Chen, Xu and Shang, 2023; Mehrabi et al., 2021; Singh et al., 2024; Ramírez-Arroyo et al., 2025).

Among satellite frequency options, C-band and Ku-band are especially relevant to tropical plantation connectivity because they exhibit materially different propagation and terminal characteristics. In broad IEEE frequency terminology, C-band occupies approximately 4–8 GHz and Ku-band approximately 12–18 GHz, although fixed-satellite service allocations occupy only portions of these generic ranges and vary by regulatory region. Lower-frequency C-band signals are generally less susceptible to precipitation attenuation, while the shorter wavelengths of Ku-band permit smaller antenna apertures for comparable directional characteristics and are widely associated with compact broadband terminals. Ku-band nevertheless experiences greater rain attenuation, an important consideration under intense equatorial rainfall. Research conducted in tropical and equatorial environments demonstrates that rain-rate distributions and attenuation models are central to Ku-band link availability and should be treated as core link-design parameters rather than marginal engineering details (Ahmad, Ismail and Badron, 2022; Al-Jumaily et al., 2022).

A crucial conceptual distinction must also be made. C-band satellite communication and C-band Synthetic Aperture Radar (SAR) remote sensing employ related frequency terminology but represent different technological functions. Communications systems transmit information between ground terminals and satellites, whereas C-band SAR actively illuminates Earth's surface and measures microwave backscatter to derive information about land cover and structure. This distinction is particularly important for oil palm because Sentinel-1 C-band SAR has demonstrated considerable value for plantation mapping under persistent tropical cloud conditions. Danylo et al. (2021), for example, used Sentinel-1 microwave data to map productive oil palm across Indonesia, Malaysia, and Thailand, while Landsat time series helped estimate plantation establishment year.

The intellectual gap addressed by this article lies precisely at the intersection of these technological domains. Satellite engineering literature typically discusses propagation, network architecture, spectrum, and link performance without examining the complete sustainability requirements of oil palm plantations. Oil palm remote-sensing literature, conversely, has become increasingly sophisticated in mapping plantations, detecting individual trees, identifying disease, and assessing environmental characteristics but usually treats the communication infrastructure required to operationalize those observations as peripheral. Smart-agriculture literature discusses IoT connectivity extensively but rarely considers the distinctive agronomic, environmental, institutional, and climatic conditions of Indonesian oil palm.

Accordingly, this review addresses four questions. First, what technical, propagation, operational, and economic characteristics distinguish C-band and Ku-band satellite technologies in tropical oil palm plantation environments? Second, how can these technologies contribute to environmental monitoring, precision agronomy, disease surveillance, harvesting, logistics, worker safety, traceability, and sustainability assurance? Third, what technological, organizational, environmental, economic, and institutional constraints may inhibit implementation? Fourth, under what circumstances should C-band, Ku-band, or hybrid satellite–terrestrial architectures be preferred? The article argues that the appropriate objective is not to identify a universally superior satellite band but to construct **fit-for-purpose connectivity architectures** capable of converting observation into verifiable sustainable management.

2. LITERATURE REVIEW

2.1. C-Band and Ku-Band as Communication Technologies

Frequency affects electromagnetic wavelength, free-space propagation characteristics, antenna dimensions, atmospheric susceptibility, available channelization, and equipment design, but frequency alone does not determine network speed. Claims that one satellite band is intrinsically “faster” than another can therefore be misleading. Actual throughput depends on allocated bandwidth, transponder or payload configuration, satellite EIRP, terminal gain, modulation and coding, spectral efficiency, contention, gateway architecture, link availability targets, and service design. For plantation managers, the relevant comparison is consequently not frequency versus frequency in isolation but the performance of complete service configurations against operational requirements.

C-band's principal attraction in tropical regions is propagation resilience. Because rain-induced attenuation becomes progressively more severe at higher microwave frequencies, C-band can maintain stronger availability margins under heavy rainfall than Ku-band when other design factors are comparable. That advantage can be valuable for fixed links connecting plantation headquarters, mills, control rooms, remote depots, or critical field gateways where service continuity is more important than terminal compactness. Its disadvantage is physical: lower frequencies generally require larger apertures to obtain comparable antenna gain and beamwidth, making conventional C-band systems less attractive for highly mobile or space-constrained applications.

Ku-band presents a different trade-off. Its shorter wavelength allows smaller directional antennas and supports practical VSAT configurations that can be installed at distributed locations or relocated more easily. Consequently, Ku-band can be attractive for temporary field camps, mobile operational teams, isolated offices, distributed smallholder service centers, and broadband applications where physical terminal size matters. Yet equatorial rainfall can significantly reduce received signal power, requiring adequate fade margins and adaptive mitigation. Ahmad, Ismail and Badron (2022) demonstrate that Ku-band attenuation coefficients in equatorial conditions require climate-sensitive treatment rather than unquestioned reliance on generic models.

The communications literature therefore points toward several mitigation mechanisms rather than outright rejection of Ku-band for tropical environments. Adaptive coding and modulation can lower spectral efficiency temporarily to preserve link continuity; uplink power control can increase transmitted power during fading; buffering and delay-tolerant transfer can defer non-critical data; traffic prioritization can preserve alarm and safety traffic; site or path redundancy can lower the probability of simultaneous outage; and hybrid terrestrial–satellite routing can divert traffic where alternative links exist. Integrated non-terrestrial network research increasingly treats satellite and terrestrial technologies as complementary layers rather than competing substitutes, while recent rural trials show that multi-connectivity can improve availability when neither terrestrial nor satellite access alone satisfies all application requirements (Rinaldi et al., 2020; Evans et al., 2021; Centenaro et al., 2021; Chen, Xu and Shang, 2023; Ramírez-Arroyo et al., 2025).

Spectrum coexistence adds another consideration. C-band frequencies are valuable not only to satellite operators but also to terrestrial mobile systems. Studies of C-band satellite earth stations show that deployment of terrestrial broadband services can create interference-management requirements, implying that plantation network planning must consider regulatory allocation, earth-station filtering, antenna discrimination, siting, and national spectrum policy in addition to propagation performance (Al-Jumaily et al., 2022). Satellite connectivity is therefore simultaneously an engineering service and a regulated infrastructure choice.

2.2. Smart Agriculture as a Layered Information System

The smart-agriculture literature provides an important conceptual correction to technology-centric approaches. A successful agricultural IoT system is not simply a collection of sensors. It is a layered information architecture involving sensing, local communications, gateway functions, storage, processing, analytics, user interfaces, and organizational action. Communication technologies must consequently be selected according to transmission range, energy consumption, latency, throughput, reliability, terrain, and application criticality. Tao et al. (2021) emphasize precisely these trade-offs and identify cost, interoperability, and reliable data management as continuing challenges.

A broad contemporary literature supports this layered view. Navarro, Costa and Pereira (2020), Idoje, Dagiuklas and Iqbal (2021), Friha et al. (2021), Yang et al. (2021), Tang et al. (2021), Sinha and Dhanalakshmi (2022), Avşar and Mowla (2022), Qazi, Khawaja and Farooq (2022), Rejeb et al. (2022), Pathmudi et al. (2023), Prakash et al. (2023), Mowla et al. (2023), Bulut and Wu (2023), Naseer et al. (2024), Shahab et al. (2024), Kumar et al. (2024), and Fuentes-Peñailillo et al. (2024) collectively show that smart agriculture integrates heterogeneous communication protocols, sensors, cloud/fog platforms, AI, UAVs, and automated equipment. They also repeatedly identify cost, skills, cybersecurity, privacy, standardization, interoperability, and incomplete rural connectivity as barriers to scaling beyond experimental deployments.

These findings are highly relevant to oil palm. Not every palm, sensor, or machine needs a direct satellite terminal. A more economical architecture can use low-power field technologies to aggregate sensor traffic at local gateways and then employ a satellite terminal for backhaul. For example, soil-moisture probes or water-table sensors might communicate through LoRa-type networks, worker devices through Wi-Fi or cellular coverage where available, and a plantation gateway could synchronize summarized data through C- or Ku-band. Such architecture reduces terminal count, energy consumption, and satellite traffic while retaining coverage advantages.

Edge computing is equally important. If every image, telemetry sample, and machinery record must be continuously transmitted to a remote cloud, satellite bandwidth requirements can become economically excessive. Edge gateways can perform local filtering, compression, anomaly detection, aggregation, and decision logic before transmission. Only abnormal measurements, priority alarms, compressed summaries, or selected imagery need immediate backhaul. This is especially useful when rain fading or service congestion temporarily constrains capacity, allowing the plantation network to degrade gracefully rather than assuming continuous unlimited broadband (Fuentes-Peñailillo et al., 2024; Shahab et al., 2024).

The social context also matters. Porciello et al. (2022) show that digital agricultural services in low- and middle-income countries frequently emphasize information and advisory functions, while evidence on broader environmental outcomes remains uneven. Socio-technical studies similarly caution that digitalization can create enabling effects alongside new dependencies, access barriers, and power asymmetries. A connection can transmit a soil measurement, but it cannot ensure that fertilizer is available, affordable, correctly formulated, or properly applied; likewise, a fire-risk alert cannot guarantee an organized response team. Digital infrastructure is therefore an enabling condition whose sustainability impact is mediated by institutional, organizational, and managerial capability (Metta et al., 2022; Hidalgo et al., 2023).

2.3. Remote Sensing and Oil Palm Intelligence

Oil palm is unusually suitable for spatially explicit digital management because plantation structure, canopy characteristics, individual trees, drainage networks, roads, riparian buffers, and surrounding land cover can be observed remotely at multiple scales. Recent literature demonstrates substantial advances in oil palm mapping using optical satellites, radar, UAVs, and machine learning. Xu et al. (2020) developed annual plantation maps for Malaysia and Indonesia; Danylo et al. (2021) combined Sentinel-1 and Landsat information; Xu et al. (2021) examined machine-learning approaches; Zeng et al. (2022) integrated open-access optical and radar data; and Pribadi et al. (2023) used high-resolution imagery and deep learning to address the difficult task of mapping fragmented smallholder plantations.

The importance of C-band SAR is especially pronounced under tropical cloud cover. Optical satellite observations can be obscured for prolonged periods, whereas radar systems actively transmit microwave energy and can acquire information through cloud cover and independent of solar illumination. Sentinel-1 therefore contributes a form of environmental observation that complements, rather than replaces, optical imagery. Ballester-Berman and Rastoll-Gimenez (2021) further demonstrate sensitivity of Sentinel-1 backscatter to oil palm characteristics over multi-year periods. The critical distinction remains that this C-band sensing capability is not the same as using C-band for satellite backhaul; one produces environmental observations while the other transports information.

At finer scales, UAVs provide centimetric or decimetric imagery useful for individual-tree assessment. Liu et al. (2021), Wibowo et al. (2022), and Putra and Wijayanto (2023) demonstrate deep-learning approaches for detecting or counting oil palm trees from high-resolution imagery. Khuzaimah et al. (2022) review drone potential and limitations in plantation contexts, while Wong et al. (2023) combine UAV observations with multicriteria sustainability assessment in smallholder plantations.

Crop-health monitoring creates another important use case. Basal stem rot caused by *Ganoderma* is a significant oil palm disease, and spectral or structural changes can become detectable before conventional visual diagnosis is reliable. Kurihara et al. (2022) examined UAV-based hyperspectral methods for early basal stem rot detection, while Ahmadi et al. (2022) evaluated UAV remote sensing for early-stage *Ganoderma* identification. Johari et al. (2023) similarly applied UAV remote sensing and machine learning to bagworm infestation mapping. These applications generate relatively large imagery datasets, making the choice between immediate transmission, local processing, delayed synchronization, and selective upload highly relevant to satellite network design.

2.4. Sustainability as a Socio-Technical Outcome

Environmental sustainability in oil palm requires more than measuring plantation boundaries. It includes avoiding further conversion of carbon-rich ecosystems, protecting riparian and conservation areas, managing peat and water responsibly, limiting fire risk, reducing unnecessary agrochemical application, and improving production on existing land. Meijaard et al. (2020) emphasize the need to evaluate palm oil within broader vegetable-oil trade-offs, while Xu et al. (2022) document recent expansion into carbon-rich forests. Bicknell et al. (2023) demonstrate that appropriately designed set-asides within oil palm landscapes can support biodiversity, carbon, and ecological functioning, and Indonesian smallholder assessments further show that sustainability must be evaluated across environmental, economic, social, institutional, and technological dimensions (Supriatna et al., 2024).

Sustainability is also agronomic. Large yield gaps mean that producing more on existing land can be possible without automatically expanding cultivated area. Monzon et al. (2023) found that average yields across the sampled Indonesian smallholder fields represented only about 42% of attainable yield and identified nutrient management, harvest interval, weed control, and pruning among key explanatory factors. Lim et al. (2023) identified inadequate and imbalanced nutrient supply as a major constraint, while de Vos et al. (2023b) showed that long harvest intervals have agronomic, socioeconomic, and institutional causes.

Yet intensification must not be interpreted as automatically sustainable. Higher profitability could, under weak land governance, increase incentives for expansion. Consequently, remote monitoring, spatial planning, tenure clarity, and enforcement must accompany productivity improvement. Gaveau et al. (2022), Astuti et al. (2022), and Xu et al. (2022) illustrate why land-use dynamics and governance remain central. Digital systems can make land-use patterns more visible, but visibility itself can produce political and governance dilemmas concerning legality, responsibility, and enforcement (Astuti et al., 2022).

Social sustainability introduces a further layer. Smallholders who cannot afford terminals, subscription fees, digital devices, training, or certification support risk being disadvantaged by increasingly data-intensive supply chains. Watts et al. (2021) show that historically excluded independent smallholders face disproportionate certification barriers and require coordinated government, private-sector, and civil-society support. Broader digital-agriculture research likewise documents unequal infrastructure access and warns that data-driven systems can reproduce asymmetries when farmers have limited control over data collection, access, and reuse (Mehrabi et al., 2021; Canfield and Ntambirweki, 2024; Amar, Bori and Cörvers, 2026). Accordingly, a sustainable satellite-enabled plantation system must be assessed not only by technical uptime but also by who can access it, who controls the data, who benefits from the resulting decisions, and who bears compliance costs.

3. METHOD

3.1. Qualitative Literature Review Design

This study employs a **qualitative literature review (QLR)** rather than a systematic literature review, bibliometric review, or meta-analysis. The choice is deliberate because the research problem extends across several disciplinary literatures that use different methods, terminology, units of analysis, and standards of evidence. Relevant studies range from telecommunications engineering and atmospheric propagation to IoT architecture, remote-sensing algorithms, plantation agronomy, environmental conservation, rural development, and sustainability governance. An interpretive synthesis is therefore more appropriate than an attempt to estimate a single pooled technological effect.

The QLR approach treats the literature as a body of conceptual and empirical evidence from which relationships, tensions, enabling conditions, and explanatory themes can be identified. It does not claim exhaustive retrieval of all literature published in a predefined universe, does not employ PRISMA-style article counting as evidence of completeness, and does not calculate pooled effect sizes. Instead, the review seeks conceptual saturation across the main components required to explain how satellite technologies could contribute to sustainable oil palm plantation management.

The initial scoping material was used only to frame the basic comparison requiring deeper investigation: relative frequency, antenna characteristics, weather sensitivity, and typical service applications of C- and Ku-band. Because simplified technical summaries can conflate generic band ranges with operational allocations and can overstate performance differences, their claims were checked against recent peer-reviewed research before being incorporated into the analytical narrative. This approach avoids, in particular, the oversimplified proposition that C-band is inherently low-speed or Ku-band inherently high-speed.

3.2. Literature Identification and Selection Logic

Literature was purposively explored across six interrelated domains: (1) C-band and Ku-band satellite communications; (2) non-terrestrial networks and satellite IoT; (3) smart-agriculture connectivity and IoT architecture; (4) oil palm remote sensing, UAVs, and machine learning; (5) oil palm agronomy and productivity; and (6) sustainability, certification, land-use governance, and smallholder inclusion. Priority was given to peer-reviewed articles published from 2020 onward in reputable indexed journals.

This purposive strategy differs fundamentally from systematic inclusion based on a single Boolean search string. The purpose was not to calculate the frequency with which particular technologies appeared in databases, but to assemble sufficient high-quality evidence to understand each link in the socio-technical chain from field observation to communication, analytical processing, management action, and sustainability verification. Forward and backward conceptual checking was used where necessary, but the final reference base reported here contains only articles from 2020 onward and only works actually cited in the manuscript.

3.3. Thematic Synthesis

The reviewed literature was interpreted through iterative thematic coding. Initial codes included frequency and propagation, terminal size, rain attenuation, bandwidth, satellite–terrestrial integration, field sensing, local gateways, edge computing, remote sensing, disease surveillance, yield gaps, harvesting, traceability, certification, environmental monitoring, smallholder barriers, cybersecurity, and data governance. These were subsequently consolidated into higher-order themes covering technical fit, plantation use cases, sustainability pathways, implementation complexity, and institutional conditions.

Cross-domain synthesis was then used to identify relationships rarely examined within a single discipline. For example, tropical rain attenuation literature was connected to the service-availability requirements of fire alarms and emergency communication; UAV disease detection literature was connected to bandwidth and edge-processing requirements; agronomic yield-gap evidence was linked to field sensing and advisory systems; and smallholder certification barriers were linked to the affordability and governance of digital traceability.

3.4. Analytical Framework and Review Rigor

Interpretation was guided by a socio-technical perspective in which technological performance was considered necessary but insufficient for sustainability outcomes. The analysis therefore distinguishes five sequential functions—Observe, Connect, Decide, Act, and Verify—and evaluates where C-band, Ku-band, terrestrial networks, remote sensing, edge processing, organizational capability, and governance enter this chain. This framing is consistent with responsible-digitalization research that treats agricultural technologies as components of broader socio-cyber-physical systems rather than isolated technical artifacts (Metta et al., 2022; Hidalgo et al., 2023).

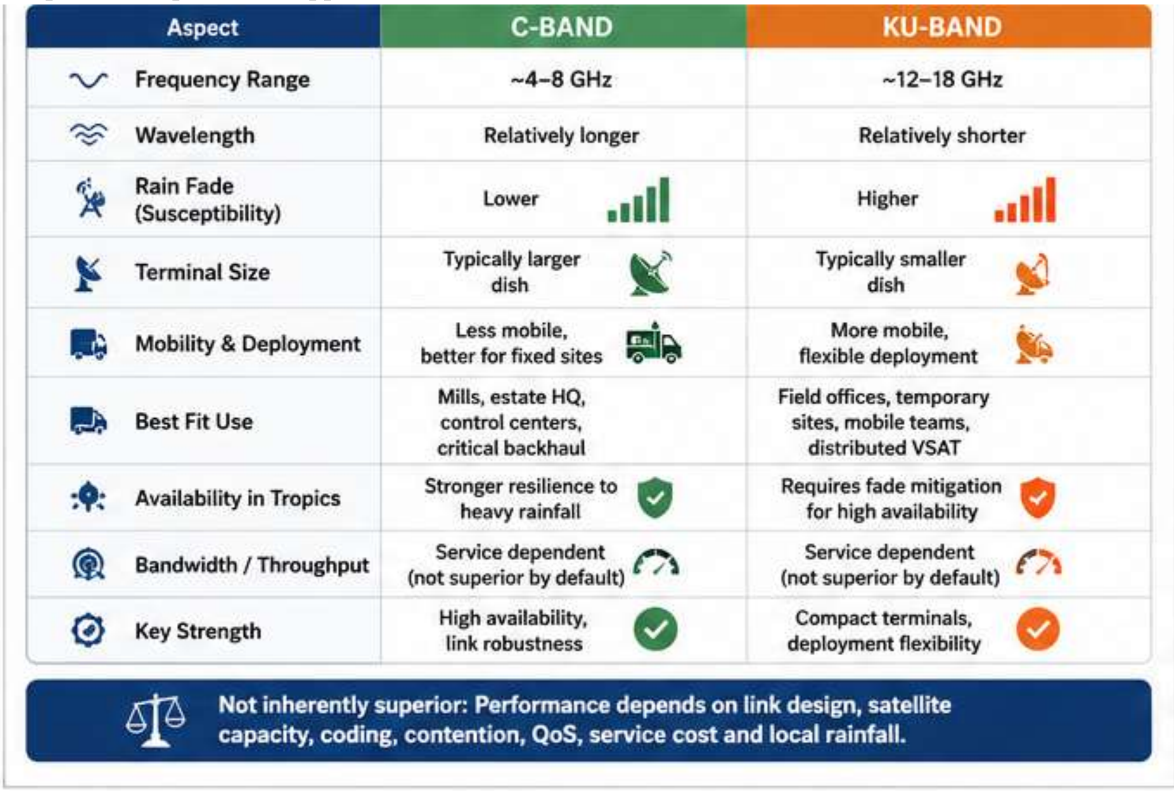
Review rigor was strengthened through source triangulation across engineering, agricultural, environmental, and governance literatures; preference for recent peer-reviewed journals; explicit attention to contradictory or conditional findings; and differentiation between evidence directly supported by empirical studies and integrative propositions developed through synthesis. This method is particularly appropriate for identifying a research agenda because many proposed satellite-enabled plantation configurations have not yet been directly compared through long-term field trials in Indonesian estates.

4. RESULTS

4.1. Theme 1: C-Band and Ku-Band Present Different but Complementary Value Propositions

The first major finding is that neither C-band nor Ku-band can be designated as universally superior for plantation connectivity. C-band's lower operating frequency provides a relative propagation advantage under heavy rainfall, making it particularly attractive where availability is mission-critical. Ku-band supports smaller terminals and often more flexible deployment, but greater rain attenuation means that tropical reliability depends strongly on link margin and mitigation strategy. The decision should therefore be driven by service-level requirements rather than by a simplistic frequency ranking (Ahmad, Ismail and Badron, 2022).

Figure 1 reframes C-band–Ku-band selection as a multidimensional trade-off rather than a binary technical contest. It highlights how rainfall resilience, terminal size, mobility, deployment context, and service design jointly determine the most appropriate option for a plantation application.



Aspect	C-BAND	KU-BAND
Frequency Range	~4–8 GHz	~12–18 GHz
Wavelength	Relatively longer	Relatively shorter
Rain Fade (Susceptibility)	Lower	Higher
Terminal Size	Typically larger dish	Typically smaller dish
Mobility & Deployment	Less mobile, better for fixed sites	More mobile, flexible deployment
Best Fit Use	Mills, estate HQ, control centers, critical backhaul	Field offices, temporary sites, mobile teams, distributed VSAT
Availability in Tropics	Stronger resilience to heavy rainfall	Requires fade mitigation for high availability
Bandwidth / Throughput	Service dependent (not superior by default)	Service dependent (not superior by default)
Key Strength	High availability, link robustness	Compact terminals, deployment flexibility

Not inherently superior: Performance depends on link design, satellite capacity, coding, contention, QoS, service cost and local rainfall.

Figure 1. Conceptual comparison of C-band and Ku-band for tropical oil palm plantation connectivity

Figure 1 makes two principles explicit. First, bandwidth and application performance cannot be inferred from band name alone. Second, terminal size and rain resilience pull network design in different directions. A plantation located in an exceptionally wet remote area may rationally accept a larger fixed terminal to secure service availability, whereas a temporary field operation may prefer a smaller Ku-band terminal and tolerate occasional throughput degradation for non-critical traffic. The optimum therefore depends on the

value of availability, not simply the price or headline data rate.

The distinction becomes more important when applications are classified by criticality. A delayed UAV image upload may be operationally acceptable, but an emergency call, fire alarm, or safety alert cannot be treated in the same manner. Similarly, daily synchronization of harvesting records may tolerate several minutes of delay, whereas a remote machinery shutdown signal may require greater reliability. Such traffic differentiation enables plantations to use satellite capacity more economically.

4.2. Theme 2: Satellite Backhaul Should Sit Above, Not Replace, Local Plantation Networks

The second theme is architectural. A sustainable plantation does not require direct satellite communication from every field device. Smart-agriculture research strongly favors heterogeneous networks in which different communication technologies perform different functions, with low-power field devices aggregated through local gateways and higher-capacity links used for backhaul (Tao et al., 2021; Tang et al., 2021; Friha et al., 2021; Avşar and Mowla, 2022; Prakash et al., 2023; Shahab et al., 2024; Kumar et al., 2024). Low-power sensors can therefore communicate locally while satellite links provide long-distance connectivity from an edge gateway.

Figure 2 synthesizes the resulting multi-layer architecture by linking field observation, local access networks, edge gateways, backhaul connectivity, analytics, and management action. The diagram also makes clear that satellite links function primarily as backhaul within a broader digital ecosystem rather than as stand-alone connections for every field device.

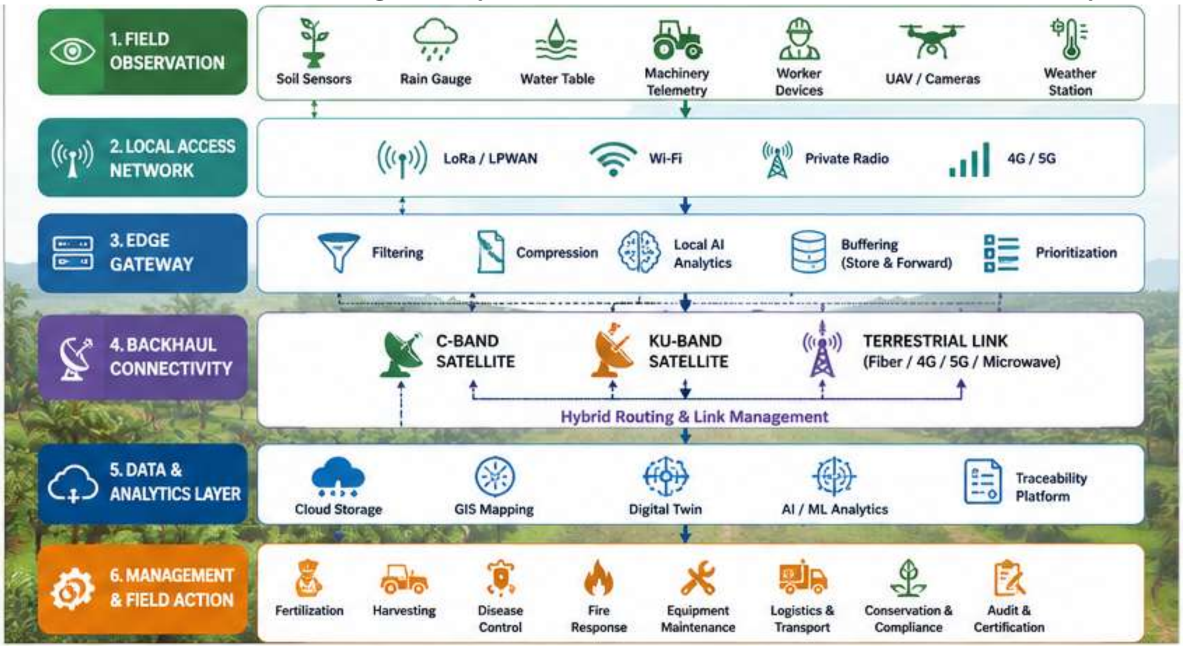


Figure 2. Satellite-enabled digital architecture for sustainable oil palm plantation management

The architecture has an important sustainability implication: the satellite link need not carry raw data continuously. Edge computing can reduce traffic volume and improve resilience. A local gateway can, for example, calculate daily water-table summaries, transmit an alert only when peat hydrology exceeds a management threshold, compress UAV imagery, or identify anomalous machinery vibration before sending a short diagnostic package. This reduces operational expenditure and permits continued local functionality during temporary loss of backhaul.

Hybrid routing also addresses the false dichotomy between satellite and terrestrial connectivity. An estate close to a cellular tower can route routine traffic terrestrially while retaining satellite as backup. A remote block can use satellite as the primary backhaul, while a mobile inspection team might use Ku-band where no cellular service exists. An estate headquarters requiring high availability might maintain C-band plus terrestrial redundancy. Integrated satellite–terrestrial research and recent rural trials provide a strong conceptual and empirical foundation for this diversity (Rinaldi et al., 2020; Evans et al., 2021; Centenaro et al., 2021; Ramírez-Arroyo et al., 2025).

4.3. Theme 3: Environmental Monitoring Is a High-Value Sustainability Application

Satellite-enabled plantation connectivity has particular value when combined with Earth observation. Remote sensing can provide spatial evidence of plantation boundaries, land-cover change, conservation areas, and surrounding forest conditions. Xu et al. (2020), Danylo et al. (2021), Xu et al.

(2021), Zeng et al. (2022), and Pribadi et al. (2023) demonstrate the rapidly growing capability to identify oil palm plantations across scales and production systems. Danylo et al.'s use of Sentinel-1 is especially important because radar can reduce the cloud-observation limitations characteristic of humid tropical regions.

This creates a two-directional information system. Earth-observation data can be delivered to plantation managers for investigation, while field teams can transmit geotagged verification observations back to central platforms. A detected land-cover anomaly may generate a task for a field officer; the officer can then submit photographs, GPS coordinates, and explanatory notes. Such closed-loop verification is more useful than remote sensing alone because algorithms inevitably encounter ambiguous boundaries, mixed land cover, shadows, topographic effects, and classification uncertainty.

Environmental monitoring can also support riparian buffers, conservation set-asides, and biodiversity management. Bicknell et al. (2023) show that spatial configuration of set-asides matters for ecological outcomes, implying that geospatial data can assist in designing and monitoring conservation interventions within productive landscapes. Satellite connectivity can additionally support camera traps, acoustic monitoring stations, ranger communications, and environmental field surveys in isolated plantation areas.

Peatland and fire management provide another compelling use case. Water-table sensors, rainfall measurements, hotspot information, local weather, and field inspection can be combined into an early-warning workflow. Here, network design must differentiate between high-volume environmental datasets and low-volume emergency alerts. A C-band or suitably engineered redundant link may be preferred for critical alarms in extremely wet locations, while bulk imagery can be transferred opportunistically. The sustainability advantage comes not from transmitting more data indiscriminately, but from matching communications priority to environmental consequence.

4.4. Theme 4: Digital Connectivity Can Support Sustainable Intensification

Agronomic evidence indicates that Indonesian smallholder oil palm productivity is constrained substantially by management rather than only by genetic planting material or biophysical potential. Monzon et al. (2023) found pronounced yield gaps and identified nutrient management, harvest interval, weed control, and pruning as important explanatory variables. Sugianto et al. (2023) likewise identify widespread nutrient deficiencies, while Lim et al. (2023) show that fertilizer supply can be both insufficient and imbalanced.

Digital systems can contribute by improving the timing, spatial targeting, documentation, and follow-up of agronomic interventions. Soil and leaf sampling locations can be georeferenced, fertilizer recommendations can be distributed digitally, application completion can be recorded by block, and anomalous crop performance can trigger inspection. Rainfall and soil-moisture information can improve timing decisions, while equipment telemetry can indicate whether spreaders or transport vehicles are operating as scheduled. Satellite backhaul becomes particularly valuable when these operations take place beyond reliable terrestrial coverage, and recent digital-agriculture reviews emphasize that such value depends on integrating sensing, communication, analytics, and actionable decision support (Shahab et al., 2024; Fuentes-Peñailillo et al., 2024).

The key term, however, is support. Connectivity cannot compensate for fertilizer unavailability, poor road access, labor shortages, limited credit, or inadequate extension services. Lim et al. (2023) explicitly emphasize the need for better nutrient management and strengthened extension. Digital communication can lower the cost and increase the reach of extension, but only when agronomic advice is trusted, locally relevant, and accompanied by access to required inputs.

Harvest management illustrates the same principle. de Vos et al. (2023b) show that long harvesting intervals among smallholders arise from agronomic, socioeconomic, and institutional factors rather than merely informational shortcomings. Digital harvest scheduling, worker allocation, geotagged harvesting records, and transport dispatch can reduce coordination failures, but the technology must operate within real labor and market constraints.

Zhao et al. (2023) further show the relevance of replanting and yield improvement strategies to longer-term production trajectories. Satellite imagery capable of distinguishing plantation age, such as the approaches demonstrated by Danylo et al. (2021), can support replanting planning when integrated with ownership, yield, and field-condition data. Thus remote sensing provides the **where and when**, connectivity provides the **information pathway**, and agronomic management provides the **productive intervention**.

4.5. Theme 5: Disease and Pest Surveillance Connect High-Resolution Sensing to Management Response

Disease detection is one of the clearest examples of why digital agriculture requires both sensing and communication. UAV hyperspectral and multispectral imagery can reveal patterns associated with *Ganoderma* infection, while machine learning can assist classification. Kurihara et al. (2022) and Ahmadi et al. (2022) demonstrate approaches for early basal stem rot detection, and Johari et al. (2023) extend machine-learning UAV analysis to bagworm infestation. The operational value of such detection depends on whether the resulting information can be delivered rapidly to managers and converted into field inspections or treatment decisions.

Raw hyperspectral imagery is data intensive, however, making permanent real-time satellite upload inefficient. A better architecture is likely to process images locally or at a nearby estate computing facility, extract georeferenced candidate locations, and transmit smaller analytical products. Full-resolution datasets can then synchronize during lower-cost or higher-capacity periods. This illustrates why a plantation's digital architecture must consider **information value per transmitted byte**.

Individual-tree detection also has operational uses beyond disease. Liu et al. (2021), Wibowo et al. (2022), and Putra and Wijayanto (2023) demonstrate automated palm-tree detection and counting from UAV or high-resolution remote-sensing imagery. These methods can assist inventory verification, stand-density analysis, missing-palm identification, replanting assessments, and potentially insurance or lending verification. When combined with field connectivity, remote observations become actionable management records rather than isolated research outputs.

4.6. Theme 6: Harvesting, Logistics, and Mill Coordination Are Strong Business-Critical Applications

Fresh fruit bunch management is highly time-sensitive compared with many annual crops because field harvesting must be coordinated with collection, transport, weighing, and milling. Satellite connectivity can support georeferenced harvest records, dispatch information, vehicle location, road-condition reporting, and synchronization between remote blocks and central management. These applications can produce direct operational benefits even before more sophisticated AI systems are adopted.

A practical plantation system can assign each harvesting block a digital task, record completion, identify uncollected fruit, and communicate transport needs to collection points. Edge devices can continue recording data offline when connectivity temporarily fails and synchronize records when the backhaul returns. This design is particularly appropriate for Ku-band services subject to short rain-induced degradation because routine transactional traffic can often tolerate temporary buffering.

Machine and vehicle monitoring similarly benefit from low-data-rate telemetry. Fuel levels, engine warnings, operating hours, tire or temperature alarms, and GPS positions require substantially less bandwidth than video. A few well-designed gateways can therefore connect many vehicles or machines through local wireless networks. The economic rationale for satellite connectivity is strongest when it simultaneously serves multiple workflows—production, safety, logistics, environmental monitoring, and administration—rather than being justified by a single application.

4.7. Theme 7: Traceability Requires Connectivity but Is Ultimately a Governance Function

Sustainability regulation and private supply-chain standards increasingly require credible information about where palm fruit originates and whether production complies with legal and environmental requirements. Geolocation, digital farm boundaries, harvest records, delivery documentation, and mill intake data can strengthen traceability, while high-resolution mapping helps identify smallholder plots that are otherwise poorly represented in official datasets (Pribadi et al., 2023). Recent oil-palm research further shows that digital and machine-learning approaches can help diagnose traceability gaps, although technical visibility must be accompanied by viable governance and implementation mechanisms (Falgenti et al., 2025).

Nevertheless, traceability should not be confused with sustainability itself. A perfectly traceable product could still originate from environmentally harmful or socially problematic production. Traceability increases observability; sustainability requires rules defining acceptable behavior, incentives to comply, and institutions capable of responding to non-compliance. Choiruzzad, Tyson and Varkkey (2021) and Putri et al. (2022) demonstrate that sustainability governance in Indonesia is embedded in wider questions of institutional coherence, policy implementation, and authority. The issue becomes particularly sensitive for smallholders. Watts et al. (2021), Apriani et al. (2020), and de Vos et al. (2023a) show that certification barriers are often structural. A digital system demanding polygon boundaries, continuous records, smartphones, broadband subscriptions, and sophisticated documentation could improve transparency for well-resourced producers while excluding those least able to comply. A sustainable digital architecture must therefore include shared mapping services, cooperative data centers, assisted registration, affordable connectivity, offline-first mobile applications, and clear procedures for correcting data errors, with explicit attention to the persistent digital divide affecting smaller farms (Mehrabi et al., 2021; Supriatna et al., 2024).

Astuti et al. (2022) provide an additional warning: making illegality visible can create difficult governance choices rather than automatically resolving them. Spatial transparency may expose overlapping land claims, administrative inconsistencies, or legacy legal problems. Plantation digitalization therefore requires procedural fairness, not only high-resolution observation.

4.8. Theme 8: Worker Safety and Social Sustainability Are Underappreciated Applications

The case for satellite connectivity is often framed around yield and automation, but remote communications can provide important social benefits. Plantation workers in isolated locations may require emergency communication after accidents, severe weather, fires, wildlife encounters, or machinery incidents. A satellite-backed network can support emergency calls, geolocation, safety check-ins, digital incident reporting, and potentially telemedicine links where terrestrial service is unavailable.

Connectivity can also support training and extension. Short instructional content, operating procedures, safety guidance, agronomic recommendations, and certification information can be delivered to remote teams. For smallholder cooperatives, shared connectivity points may provide access not only to farm management platforms but also to administrative, financial, educational, and government services.

However, worker connectivity can become worker surveillance if governance is poorly designed. Continuous location tracking, productivity scoring, biometric attendance, and automated performance analysis can create privacy and power concerns. Smart-agriculture research increasingly emphasizes cybersecurity, privacy, recognition, and data-rights risks, particularly where digital systems redistribute control without meaningful participation by workers or farmers (Yang et al., 2021; Qazi, Khawaja and Farooq, 2022; Naseer et al., 2024; Carolan, 2024; Canfield and Ntambirweki, 2024; Sullivan et al., 2024). Sustainable plantation digitalization therefore requires transparent data policies, purpose limitation, appropriate access control, and mechanisms allowing workers and smallholders to understand and contest how their information is used.

4.9. Theme 9: Implementation Challenges Extend Far Beyond Rain Fade

Rain attenuation is an important technological constraint but not the only one. Satellite terminals require stable power, secure physical installation, appropriate line of sight, maintenance capability, and trained technicians. Remote oil palm areas may experience unreliable electricity, difficult road access, lightning, heat, humidity, insects, corrosion, or equipment theft. Designing a technically sophisticated link without maintenance capacity can therefore create fragile infrastructure, a concern consistent with broader smart-agriculture evidence on infrastructure, skills, connectivity, and system-maintenance barriers (Kumar et al., 2024; Shahab et al., 2024).

Cost is equally consequential. Capital expenditure includes terminal hardware, installation, mounting, power conditioning, backup batteries, local networking equipment, and potentially environmental protection. Operating expenditure includes bandwidth or service subscriptions, maintenance, licensing where applicable, and equipment replacement. For independent smallholders, individual satellite installations are unlikely to be economical in many contexts, especially where the broader digital divide already reflects disparities in connectivity access and affordability. Shared cooperative gateways or service-provider-managed infrastructure may therefore be more viable (Mehrabi et al., 2021).

Interoperability is another recurring problem. Plantation companies often possess multiple legacy systems covering finance, mill operations, GIS, human resources, fleet management, and certification. New IoT platforms can generate additional proprietary data silos rather than integration. Smart-agriculture reviews consistently identify interoperability and standardization as scaling challenges, while agricultural data-sharing research shows that trust is also weakened when stakeholders lack clarity about technical compatibility, data access, privacy, and governance (Tao et al., 2021; Bulut and Wu, 2023; Pathmudi et al., 2023; Sullivan et al., 2024).

Cybersecurity becomes more important as field devices can influence physical operations. Compromised sensors could generate false environmental readings; stolen credentials could alter harvest records; ransomware could disrupt mill–estate coordination; manipulated traceability records could undermine certification; and insecure remote-control systems could pose safety risks. Yang et al. (2021) identify authentication, access control, cryptography, intrusion detection, and privacy protection as essential smart-agriculture considerations, while Sullivan et al. (2024) show that privacy, security, and data sovereignty are central barriers to agricultural data sharing.

Finally, spectrum and regulatory conditions can affect infrastructure deployment. C-band satellite earth stations may face coexistence challenges with terrestrial systems occupying nearby frequencies, while satellite services themselves depend on national licensing and operator availability. Al-Jumaily et al. (2022) show why coexistence analysis is technically significant. Plantation connectivity planning should therefore involve telecommunications expertise rather than treating VSAT procurement as an ordinary IT purchase.

5. DISCUSSION AND ANALYSIS

5.1. RQ1: What Fundamentally Distinguishes C-Band and Ku-Band in Indonesian Plantation Conditions?

The review indicates that the most consequential difference is not nominal data speed but the combination of **rain sensitivity, terminal geometry, deployment flexibility, and service economics**. C-band generally provides a stronger propagation margin in heavy tropical precipitation, whereas Ku-band makes compact terminals more practical. These characteristics favor different operational niches.

For an estate headquarters or mill requiring continuously available connectivity, especially in high-rainfall regions without robust terrestrial alternatives, the higher physical footprint of C-band may be acceptable in exchange for greater rain resilience. Conversely, a smaller Ku-band terminal may be preferable for temporary field facilities, isolated collection centers, inspection teams, or rapidly deployed connectivity. With sufficient fade margin, adaptive coding, traffic prioritization, and backup links, Ku-band can still support demanding tropical operations.

The decision must therefore begin with an application inventory. Plantation managers should determine required uptime, throughput, latency, mobility, data criticality, available power, antenna space, local rainfall, terrestrial-network availability, and budget. Frequency selection follows these requirements rather than preceding them.

5.2. RQ2: How Do Satellite Technologies Contribute to Sustainable Plantation Management?

The literature suggests that satellite connectivity affects sustainability indirectly through an information-action pathway. A signal transmitted successfully through C- or Ku-band has no inherent environmental value. Value emerges when connectivity improves the quality, timeliness, accessibility, or verifiability of information and that information changes management. This relationship can be summarized as a causal sequence in which connectivity improves information availability, which supports better diagnosis and coordination, enables managerial action, and—when implementation and governance are effective—can contribute to measurable sustainability outcomes (Metta et al., 2022; Hidalgo et al., 2023).

Examples clarify the distinction. A water-table sensor contributes nothing if readings remain inaccessible; connectivity makes them available, analytics identify abnormal conditions, and field teams alter drainage management. A satellite image may identify suspected land-cover change; connectivity transmits the alert, a field team verifies it, and management prevents unauthorized clearing. A nutrient database identifies deficiency; digital extension communicates a recommendation, and farmers adjust fertilizer practice. Each outcome depends on all links being functional.

Figure 3 presents the central conceptual contribution of this review: the Observe–Connect–Decide–Act–Verify framework. The framework organizes satellite-enabled plantation management as a feedback cycle in which sensing and connectivity become valuable only when they support decisions, field action, outcome verification, and subsequent learning.

Figure 3. The Observe–Connect–Decide–Act–Verify framework

The framework addresses a common weakness in discussions of digital sustainability: they often stop at observation. Remote sensing can show where plantations are located, IoT can measure field conditions, and satellite networks can move the data, but sustainability requires decision rules, responsible actors, operational capacity, and verification of resulting outcomes. The feedback loop is therefore essential because verification generates new observations, reveals whether interventions worked, and supports adaptive management. This emphasis on interactions among technical, organizational, and social components is consistent with responsible-digitalization frameworks that reject purely technology-centric assessments (Metta et al., 2022; Hidalgo et al., 2023).

5.3. RQ3: Why Is Implementation More Complex Than Satellite Procurement?

The principal barriers fall into five interacting categories. First are environmental constraints, particularly tropical rainfall, lightning exposure, humidity, and difficult physical access. Second are technological constraints, including power supply, terminal maintenance, cybersecurity, interoperability, and integration with legacy systems. Third are economic constraints, including equipment cost, service fees, and uncertain return on investment. Fourth are organizational constraints, particularly limited digital skills, weak data governance, fragmented responsibilities, and insufficient technical support. Fifth are institutional constraints, including land legality, certification complexity, spectrum regulation, unequal smallholder capacity, and ambiguous accountability. Comparable multi-dimensional barriers recur across recent smart-agriculture and Indonesian smallholder sustainability research (Kumar et al., 2024; Supriatna et al., 2024).

These barriers reinforce one another. A cheaper terminal has limited value without trained maintenance staff. High-quality environmental data cannot resolve a land dispute if there is no legitimate adjudication process, and a traceability system can marginalize farmers when land documents are incomplete. Higher sensor density can likewise create more data without creating better decisions. For this reason, Bulut and Wu (2023), Pathmudi et al. (2023), Rejeb et al. (2022), Porciello et al. (2022), Mehrabi et al. (2021), and Amar, Bori and Cörvers (2026) are important complements to purely technical satellite literature because they show that agricultural digitalization can fail or become exclusionary when organizational, infrastructural, and data-governance conditions are treated as residual concerns.

5.4. RQ4: When Should C-Band, Ku-Band, or Hybrid Systems Be Preferred?

The synthesis suggests that connectivity should be matched to plantation archetype and operational mission rather than standardized across all estates. This fit-for-purpose approach recognizes that estate scale, terrestrial coverage, rainfall exposure, terminal mobility, traffic criticality, power availability, and budget can materially alter the preferred architecture (Ramírez-Arroyo et al., 2025).

A large industrial estate with fixed mills, central offices, high-value databases, and extensive IoT infrastructure may justify a highly available C-band backbone, terrestrial fiber or microwave where available, and Ku-band or cellular links for distributed field locations. A medium-sized estate might obtain better economics from a Ku-band VSAT combined with local LoRaWAN and a backup cellular connection. An independent smallholder cooperative is more likely to benefit from a shared connectivity hub than individual satellite terminals. A remote environmental-monitoring station may transmit only small telemetry packets and therefore prioritize reliability and energy efficiency over throughput, whereas a mobile field team may prioritize antenna portability and rapid installation. These differentiated configurations are consistent with evidence that rural connectivity performs best when terrestrial and non-terrestrial links are combined according to application requirements rather than imposed as a single universal solution (Ramírez-Arroyo et al., 2025; Singh et al., 2024).

Figure 4 translates these findings into a fit-for-purpose decision framework for plantation connectivity. It structures the choice around terrestrial availability, mission criticality, rainfall exposure, mobility, traffic type, and smallholder context rather than assuming that one satellite band is universally optimal.

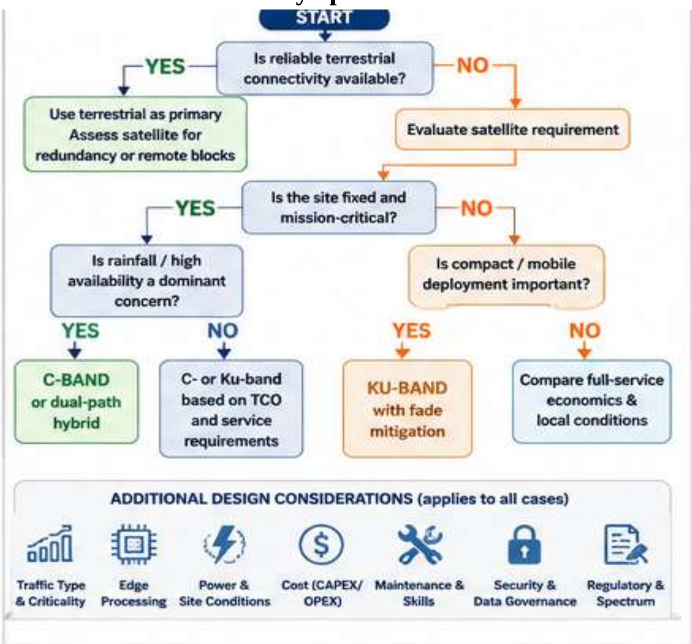


Figure 4. Fit-for-purpose decision logic for plantation satellite connectivity

The framework deliberately avoids deterministic recommendations. Local satellite availability, operator pricing, orbital architecture, antenna technology, terrain, rain climatology, national regulation, and terrestrial infrastructure can change the optimal configuration. Consequently, any actual investment should be preceded by a site-specific link budget and total-cost-of-ownership analysis that also considers application criticality and the feasibility of hybrid terrestrial–satellite operation (Ahmad, Ismail and Badron, 2022; Ramírez-Arroyo et al., 2025).

5.5. Sustainable Intensification Requires Environmental Guardrails

One of the strongest potential benefits of digital plantation management is narrowing yield gaps on existing land. Monzon et al. (2023), Lim et al. (2023), Sugianto et al. (2023), de Vos et al. (2023b), and Zhao et al. (2023) collectively demonstrate opportunities associated with improved agronomic management, nutrient supply, harvesting, and replanting. Better connectivity can make extension, monitoring, and coordination more scalable.

Nevertheless, a rebound risk exists. If digital agriculture increases profitability but land governance remains weak, higher returns can theoretically strengthen incentives for expansion. The correct policy response is therefore not to reject productivity technology but to pair intensification with land-use monitoring, spatial planning, conservation requirements, and credible enforcement. Remote sensing is especially well suited to this coupling because the same digital transformation that improves agronomy can also improve detection of land-cover change.

Gaveau et al. (2022) show that patterns of deforestation and oil palm expansion respond to broader market and governance conditions, while Xu et al. (2022) document continuing concerns about expansion into carbon-rich forests. Environmental additionality should therefore be demonstrated using outcomes such as stable plantation boundaries, protected riparian areas, reduced fire incidence, improved water management, reduced unnecessary input use, or improved ecological condition—not inferred merely from installation of digital equipment.

5.6. Smallholder Inclusion Should Be Designed into the Architecture

Digital inclusion is arguably the most important governance challenge for satellite-enabled sustainability. Large plantations can distribute infrastructure costs over thousands of hectares, employ IT departments, and negotiate enterprise connectivity contracts, whereas independent smallholders cannot necessarily do so. If future traceability regimes require continuous connectivity and technically complex data records, digital compliance could create a new barrier layered on top of existing legal and certification barriers documented by Watts et al. (2021) and de Vos et al. (2023a). The global farming connectivity divide and emerging data-governance literature reinforce this concern by showing that small farms often face weaker network access and less control over the data infrastructures in which they participate (Mehrabi et al., 2021; Canfield and Ntambirweki, 2024; Amar, Bori and Cörvers, 2026).

A more inclusive design would treat connectivity as shared rural infrastructure. Cooperatives, village institutions, mills, service providers, or public–private programs could operate gateways serving multiple farmers. A single satellite link could support farm registration, extension, traceability, digital payments, market information, environmental monitoring, and government services. The economics become more favorable as fixed connectivity costs are distributed across users and applications, while networked-farm research suggests that shared connectivity can also support coordination and information exchange beyond the individual farm (Mehrabi et al., 2021; Singh et al., 2024).

Data governance must accompany sharing. Smallholders should understand what information is collected, who can access it, how inaccuracies can be corrected, and whether data might affect eligibility for markets, finance, or certification. A farm polygon that is wrong by several meters can have serious consequences when overlaid with forest-estate boundaries or protected areas. Human review and appeal mechanisms therefore remain essential, and recent research on agricultural data sharing and smallholder data governance underscores the importance of trust, farmer rights, consent, and meaningful mechanisms for redress (Sullivan et al., 2024; Canfield and Ntambirweki, 2024; Amar, Bori and Cörvers, 2026).

5.7. C-Band SAR and Satellite Communications Should Be Integrated Conceptually but Kept Technically Distinct

One of the article's central conceptual contributions is to show that two uses of "C-band" can reinforce each other while remaining technically distinct. Sentinel-1 C-band SAR can repeatedly observe plantation landscapes through cloud, while C-band communications can provide robust backhaul for field data in rainy environments. The first generates spatial evidence; the second moves operational information.

An advanced plantation information system could combine them. A Sentinel-1 algorithm might identify changes in plantation structure; a cloud or central GIS system generates an anomaly; that anomaly is transmitted to an estate through the available backhaul; field staff inspect the location and submit geotagged evidence; the evidence becomes part of a compliance record. In this workflow, SAR, C-/Ku-band communications, mobile devices, edge processing, and governance procedures are complementary components of one information chain.

This integration is particularly promising for independent sustainability verification. Danylo et al. (2021) demonstrate the capacity of radar-based mapping to produce extensive spatial information independent of ground-sourced official statistics, while Pribadi et al. (2023) show the possibility of high-resolution smallholder mapping. Such technologies can increase transparency, but Astuti et al. (2022) remind us that visibility must be accompanied by fair governance.

5.8. Toward a Dual-Layer Resilience Architecture

The synthesis supports a broader proposition for tropical plantation digitalization: critical operations may benefit from a **dual-layer resilience architecture**. The first layer is a high-availability pathway for safety alarms, environmental alerts, essential business transactions, and emergency communication. Depending on site conditions, C-band or redundant satellite–terrestrial connectivity may be appropriate. The second layer is a flexible broadband pathway for imagery, software updates, routine administrative data, and non-critical synchronization, potentially using Ku-band or terrestrial broadband.

Traffic classes can then be assigned priorities. A fire alert might receive immediate transmission regardless of cost. A compressed disease-detection result might be sent promptly. Full UAV imagery could wait for off-peak bandwidth or a terrestrial connection. Routine sensor histories could synchronize once daily. This architecture makes satellite connectivity economically efficient because scarce link capacity is allocated according to managerial consequence.

Figure 5 summarizes the sustainability pathways and the conditions that determine whether connectivity becomes a genuine enabling capability or merely another technology cost. It emphasizes that environmental, economic, social, and governance outcomes are moderated by affordability, skills, climate, infrastructure, institutions, land tenure, inclusion, and data rights.

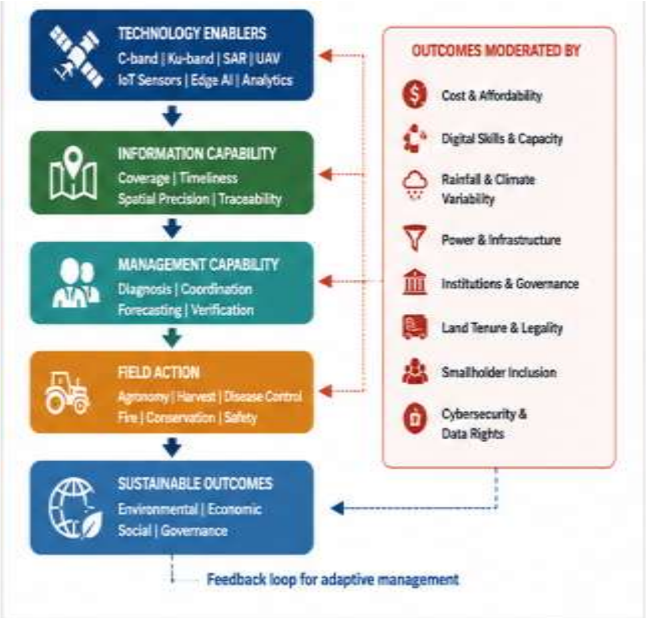


Figure 5. From satellite connectivity to sustainable plantation outcomes

Figure 5 clarifies why the article does not treat satellite technology as intrinsically sustainable. Sustainability benefits are contingent on the intermediate management system. A technically excellent connection may yield little benefit if information is not acted upon, while a relatively modest low-bandwidth service can be highly valuable when it supports critical environmental and safety decisions.

5.9. Policy Implications for Indonesia

Several policy implications follow. First, rural connectivity strategies should recognize productive landscapes as infrastructure users rather than viewing telecommunications only through household population density. Remote plantation areas can support economic production, environmental monitoring, and public safety even where conventional consumer-market calculations make terrestrial infrastructure unattractive. Evidence on the global agricultural digital divide, smart connected farms, and terrestrial–satellite multi-connectivity supports policy approaches that treat reliable rural coverage as an enabling infrastructure for data-intensive agricultural services (Mehrabi et al., 2021; Singh et al., 2024; Ramírez-Arroyo et al., 2025).

Second, satellite infrastructure for smallholders should be evaluated as a shared service. Connectivity hubs linked to cooperatives, mills, extension centers, or village institutions can reduce per-farmer cost while supporting multiple functions. Public intervention may be justified where connectivity produces environmental-monitoring, traceability, extension, and inclusion benefits that extend beyond private farm income, particularly in smallholder systems where sustainability challenges span technological, institutional, social, and economic dimensions (Supriatna et al., 2024; Mehrabi et al., 2021).

Third, interoperability standards deserve greater attention than vendor-specific platforms. Agricultural sensors, GIS systems, traceability platforms, remote-sensing products, and certification records should exchange data using documented interfaces and portable formats. Otherwise, plantations risk becoming dependent on closed technology ecosystems that are expensive to maintain or replace, while limited interoperability can also reduce stakeholder willingness to share data across organizational boundaries (Sullivan et al., 2024; Shahab et al., 2024).

Fourth, cybersecurity and data protection should be embedded during system design. The digitization of land boundaries, production records, worker locations, machinery, and financial transactions creates valuable datasets. Authentication, role-based access, secure software updates, encryption, audit logs, backup procedures, and incident response are therefore integral to sustainability governance rather than merely IT administration. Equally important are transparent data rights, consent, access rules, and redress mechanisms because technical security alone does not resolve asymmetries in agricultural data governance (Sullivan et al., 2024; Canfield and Ntambirweki, 2024; Amar, Bori and Cörvers, 2026).

Fifth, spectrum planning and satellite policy should consider the continuing importance of fixed satellite links in remote productive areas. C-band coexistence decisions should recognize high-rainfall regions where lower-frequency satellite connectivity may provide resilience advantages that are difficult to replicate with higher-frequency links.

5.10. Research Agenda

The reviewed literature contains relatively few direct C-band versus Ku-band field comparisons within commercial tropical plantation operations. Future research should therefore conduct multi-season trials across representative Indonesian rainfall regimes, measuring actual availability, throughput, latency, fade events, energy consumption, maintenance requirements, and total cost of ownership. Nominal service specifications are insufficient for mission-critical agricultural design.

A second priority is application-level economic analysis. Researchers should estimate how much connectivity value arises from specific workflows—reduced harvest delay, earlier disease detection, lower monitoring cost, improved machinery utilization, fewer unnecessary field visits, environmental compliance, or improved worker safety. This would enable investment decisions to move beyond generic claims that "digitalization improves efficiency."

Third, satellite IoT architectures specifically designed for independent oil palm smallholders merit investigation. Comparative trials could evaluate individual terminals, cooperative gateways, mill-centered networks, and public rural connectivity hubs. Outcomes should include affordability, participation, digital literacy, gendered access, data ownership, and certification inclusion, not merely packet-delivery statistics.

Fourth, data-fusion research could integrate C-band SAR, optical imagery, UAV observations, field IoT data, production records, and environmental indicators. Such multimodal systems may improve detection of disease, drainage problems, abnormal yield, land-cover change, and replanting needs. Edge AI could reduce satellite bandwidth requirements by processing imagery close to the source.

Finally, longitudinal studies are required to test whether digital connectivity actually produces environmental and social additionality. The most important questions concern outcomes: Does fertilizer efficiency improve? Are fires detected earlier? Are conservation areas better protected? Do smallholders gain or lose market access? Are worker accidents responded to more rapidly? Does greater productivity reduce pressure for expansion, or does profitability create a rebound effect? These questions would move research from technological possibility toward verified sustainability impact.

6. CONCLUSION

This qualitative literature review demonstrates that C-band and Ku-band satellite technologies can become important components of sustainable oil palm plantation management in Indonesia, but their value arises from **fit with operational context**, not from inherent superiority of one frequency band. C-band offers a relative advantage in resistance to tropical rain attenuation and is therefore particularly relevant to fixed, high-availability links. Ku-band supports smaller and more deployable terminals and can provide flexible broadband access, but its tropical use requires deliberate management of rain fade. Throughput, reliability, and economic performance ultimately depend on the complete satellite service and link architecture rather than frequency alone.

Satellite connectivity can support numerous sustainability-related functions: plantation mapping, environmental surveillance, IoT telemetry, precision nutrient management, drainage monitoring, disease detection, harvesting, logistics, worker safety, traceability, certification, and emergency response. Yet these benefits are indirect. Connectivity produces sustainability only when data are converted into sound decisions and effective field action.

The review therefore proposes an **Observe–Connect–Decide–Act–Verify** model. Remote sensing, UAVs, sensors, and workers first observe plantation conditions; C-band, Ku-band, terrestrial systems, or hybrid networks connect observations to decision systems; analytics and human expertise convert information into decisions; field operations act; and monitoring verifies outcomes. The cycle then generates new observations for adaptive management.

For Indonesia, a hybrid architecture is generally more defensible than universal reliance on either C- or Ku-band. Local low-power networks can aggregate field data, edge gateways can filter and prioritize traffic, satellite links can bridge coverage gaps, and terrestrial networks can carry traffic wherever economically available. Critical and routine traffic should receive different service priorities. Large estates can deploy enterprise architectures, whereas independent smallholders are more likely to benefit from shared cooperative or village connectivity.

Most importantly, digitalization must not intensify existing inequalities. Smallholder affordability, institutional capacity, data rights, cybersecurity, legal ambiguity, and access to extension remain central determinants of success. Satellite technology should therefore be viewed neither as a sustainability solution in itself nor merely as communications infrastructure. Properly designed, it is an enabling layer that can connect spatial observation, agronomic knowledge, operational coordination, environmental accountability, and inclusive governance across geographically dispersed plantation landscapes.

REFERENCES

1. Ahmad, Y.A., Ismail, A.F. and Badron, K. (2022) 'Ku-band specific attenuation coefficients for high-throughput satellites in equatorial region', *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 20(4), pp. 722–730. Available at: https://doi.org/10.12928/telkomnika.v20i4.23766.
2. Ahmadi, P. et al. (2022) 'Unmanned Aerial Vehicle (UAV)-based remote sensing for early-stage detection of Ganoderma', *Remote Sensing*, 14(5), 1239. Available at: https://doi.org/10.3390/rs14051239.
3. Al-Jumaily, A. et al. (2022) 'Evaluation of 5G coexistence and interference signals in the C-band satellite earth station', *IEEE Transactions on Vehicular Technology*, 71(6), pp. 6189–6200. Available at: https://doi.org/10.1109/TVT.2022.3158344.
4. Amar, S., Bori, N. and Cörvers, R. (2026) 'From collection to control: Data governance, digital technologies, and the politics of inclusion in the digitalisation of smallholder agriculture', *Outlook on Agriculture*, 55(1), pp. 19–27. Available at: https://doi.org/10.1177/00307270251410944.
5. Apriani, E. et al. (2020) 'Non-state certification of smallholders for sustainable palm oil in Sumatra, Indonesia', *Land Use Policy*, 99, 105112. Available at: https://doi.org/10.1016/j.landusepol.2020.105112.
6. Astuti, R. et al. (2022) 'Making illegality visible: The governance dilemmas created by visualising illegal palm oil plantations in Central Kalimantan, Indonesia', *Land Use Policy*, 114, 105942. Available at: https://doi.org/10.1016/j.landusepol.2021.105942.
7. Avşar, E. and Mowla, M.N. (2022) 'Wireless communication protocols in smart agriculture: A review on applications, challenges and future trends', *Ad Hoc Networks*, 136, 102982. Available at: https://doi.org/10.1016/j.adhoc.2022.102982.
8. Ayompe, L.M., Schaafsma, M. and Egoh, B.N. (2021) 'Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing', *Journal of Cleaner Production*, 278, 123914. Available at: https://doi.org/10.1016/j.jclepro.2020.123914.
9. Ballester-Berman, J.D. and Rastoll-Gimenez, M. (2021) 'Sensitivity analysis of Sentinel-1 backscatter to oil palm plantations at pluriannual scale: A case study in Gabon, Africa', *Remote Sensing*, 13(11), 2075. Available at: https://doi.org/10.3390/rs13112075.
10. Bicknell, J.E. et al. (2023) 'Enhancing the ecological value of oil palm agriculture through set-asides', *Nature Sustainability*, 6, pp. 513–525. Available at: https://doi.org/10.1038/s41893-022-01049-6.
11. Bulut, C. and Wu, P.F. (2023) 'More than two decades of research on IoT in agriculture: A systematic literature review', *Internet Research*, 34(3), pp. 994–1016. Available at: https://doi.org/10.1108/INTR-07-2022-0559.
12. Canfield, M. and Ntambirweki, B. (2024) 'Datafying African agriculture: From data governance to farmers' rights', *Development*, 67(1), pp. 5–13. Available at: https://doi.org/10.1057/s41301-024-00405-7.
13. Carolan, M. (2024) 'Who and what gets recognized in digital agriculture: Agriculture 4.0 at the intersectionality of (Dis)Ableism, labor, and recognition justice', *Agriculture and Human Values*, 41(4), pp. 1465–1480. Available at: https://doi.org/10.1007/s10460-024-10560-9.
14. Centenaro, M. et al. (2021) 'A survey on technologies, standards and open challenges in satellite IoT', *IEEE Communications Surveys & Tutorials*, 23(3), pp. 1693–1720. Available at: https://doi.org/10.1109/COMST.2021.3078433.
15. Chen, X., Xu, Z. and Shang, L. (2023) 'Satellite Internet of Things: Challenges, solutions, and development trends', *Frontiers of Information Technology & Electronic Engineering*, 24, pp. 935–944. Available at: https://doi.org/10.1631/FITEE.2200648.
16. Choiruzzad, S.A.B., Tyson, A. and Varkkey, H. (2021) 'The ambiguities of Indonesian Sustainable Palm Oil certification: Internal incoherence, governance rescaling and state transformation', *Asia Europe Journal*, 19(2), pp. 189–208. Available at: https://doi.org/10.1007/s10308-020-00593-0.
17. Danylo, O. et al. (2021) 'A map of the extent and year of detection of oil palm plantations in Indonesia, Malaysia and Thailand', *Scientific Data*, 8, 96. Available at: https://doi.org/10.1038/s41597-021-00867-1.
18. de Vos, R.E. et al. (2023a) 'Pre-certification conditions of independent oil palm smallholders in Indonesia: Assessing prospects for RSPO certification', *Land Use Policy*, 130, 106660. Available at: https://doi.org/10.1016/j.landusepol.2023.106660.
19. de Vos, R.E. et al. (2023b) 'Shortening harvest interval, reaping benefits? A study on harvest practices in oil palm smallholder farming systems in Indonesia', *Agricultural Systems*, 211, 103753. Available at:

https://doi.org/10.1016/j.agsy.2023.103753.

20. Evans, B. et al. (2021) 'An integrated satellite–terrestrial 5G network and its use to demonstrate 5G use cases', *International Journal of Satellite Communications and Networking*, 39, pp. 358–379. Available at: https://doi.org/10.1002/sat.1393.
21. Falgenti, K. et al. (2025) 'Enhancing traceability and sustainability in smallholder oil palm plantations through gap analysis and machine learning', *ASEAN Journal on Science and Technology for Development*, 43(1), Article 11. Available at: https://doi.org/10.61931/2224-9028.1637.
22. Friha, O. et al. (2021) 'Internet of Things for the future of smart agriculture: A comprehensive survey of emerging technologies', *IEEE/CAA Journal of Automatica Sinica*, 8(4), pp. 718–752. Available at: https://doi.org/10.1109/JAS.2021.1003925.
23. Fuentes-Peñailillo, F. et al. (2024) 'Transformative technologies in digital agriculture: Leveraging Internet of Things, remote sensing, and artificial intelligence for smart crop management', *Journal of Sensor and Actuator Networks*, 13(4), 39. Available at: https://doi.org/10.3390/jsan13040039.
24. Gaveau, D.L.A. et al. (2022) 'Slowing deforestation in Indonesia follows declining oil palm expansion and lower oil prices', *PLOS ONE*, 17(3), e0266178. Available at: https://doi.org/10.1371/journal.pone.0266178.
25. Hidalgo, F. et al. (2023) 'Digitalization, sustainability, and coffee: Opportunities and challenges for agricultural development', *Agricultural Systems*, 208, 103660. Available at: https://doi.org/10.1016/j.agsy.2023.103660.
26. Idoje, G., Dagiuklas, T. and Iqbal, M. (2021) 'Survey for smart farming technologies: Challenges and issues', *Computers & Electrical Engineering*, 92, 107104. Available at: https://doi.org/10.1016/j.compeleceng.2021.107104
27. Johari, S.N.A.M. et al. (2023) 'Detection of bagworm infestation area in oil palm plantation based on UAV remote sensing using machine learning approach', *Agriculture*, 13(10), 1886. Available at: https://doi.org/10.3390/agriculture13101886.
28. Khuzaimah, Z. et al. (2022) 'Application and potential of drone technology in oil palm plantation: Potential and limitations', *Journal of Sensors*, 2022, 5385505. Available at: https://doi.org/10.1155/2022/5385505.
29. Kumar, V. et al. (2024) 'A comprehensive review on smart and sustainable agriculture using IoT technologies', *Smart Agricultural Technology*, 8, 100487. Available at: https://doi.org/10.1016/j.atech.2024.100487.
30. Kurihara, J. et al. (2022) 'Early detection of basal stem rot disease in oil palm tree using unmanned aerial vehicle-based hyperspectral imaging', *Remote Sensing*, 14(3), 799. Available at: https://doi.org/10.3390/rs14030799.
31. Lim, Y.L. et al. (2023) 'Too little, too imbalanced: Nutrient supply in smallholder oil palm fields in Indonesia', *Agricultural Systems*, 210, 103729. Available at: https://doi.org/10.1016/j.agsy.2023.103729.
32. Liu, X. et al. (2021) 'Automatic detection of oil palm tree from UAV images based on the deep learning method', *Applied Artificial Intelligence*, 35(1), pp. 13–24. Available at: https://doi.org/10.1080/08839514.2020.1831226.
33. Mehrabi, Z. et al. (2021) 'The global divide in data-driven farming', *Nature Sustainability*, 4, pp. 154–160. Available at: https://doi.org/10.1038/s41893-020-00631-0.
34. Meijaard, E. et al. (2020) 'The environmental impacts of palm oil in context', *Nature Plants*, 6, pp. 1418–1426. Available at: https://doi.org/10.1038/s41477-020-00813-w.
35. Metta, M. et al. (2022) 'An integrated socio-cyber-physical system framework to assess responsible digitalisation in agriculture: A first application with Living Labs in Europe', *Agricultural Systems*, 203, 103533. Available at: https://doi.org/10.1016/j.agsy.2022.103533.
36. Monzon, J.P. et al. (2023) 'Agronomy explains large yield gaps in smallholder oil palm fields', *Agricultural Systems*, 210, 103689. Available at: https://doi.org/10.1016/j.agsy.2023.103689.
37. Mowla, M.N. et al. (2023) 'Internet of Things and wireless sensor networks for smart agriculture applications: A survey', *IEEE Access*, 11, pp. 145813–145852. Available at: https://doi.org/10.1109/ACCESS.2023.3346299.
38. Naseer, A. et al. (2024) 'A systematic literature review of the IoT in agriculture—global adoption, innovations, security, and privacy challenges', *IEEE Access*, 12, pp. 60986–61021. Available at: https://doi.org/10.1109/ACCESS.2024.3394617.
39. Navarro, E., Costa, N. and Pereira, A. (2020) 'A systematic review of IoT solutions for smart farming', *Sensors*, 20(15), 4231. Available at: https://doi.org/10.3390/s20154231.
40. Pathmudi, V.R. et al. (2023) 'A systematic review of IoT technologies and their constituents for smart and sustainable agriculture applications', *Scientific African*, 19, e01577. Available at: https://doi.org/10.1016/j.sciaf.2023.e01577.

41. Porciello, J. et al. (2022) 'Digital agriculture services in low- and middle-income countries: A systematic scoping review', *Global Food Security*, 34, 100640. Available at: https://doi.org/10.1016/j.gfs.2022.100640.
42. Prakash, C. et al. (2023) 'Advancements in smart farming: A comprehensive review of IoT, wireless communication, sensors, and hardware for agricultural automation', *Sensors and Actuators A: Physical*, 362, 114605. Available at: https://doi.org/10.1016/j.sna.2023.114605.
43. Pribadi, D.O. et al. (2023) 'Mapping smallholder plantation as a key to sustainable oil palm: A deep learning approach to high-resolution satellite imagery', *Applied Geography*, 154, 102921. Available at: https://doi.org/10.1016/j.apgeog.2023.102921.
44. Putra, Y.C. and Wijayanto, A.W. (2023) 'Automatic detection and counting of oil palm trees using remote sensing and object-based deep learning', *Remote Sensing Applications: Society and Environment*, 29, 100914. Available at: https://doi.org/10.1016/j.rsase.2022.100914.
45. Putri, E.I.K. et al. (2022) 'The oil palm governance: Challenges of sustainability policy in Indonesia', *Sustainability*, 14(3), 1820. Available at: https://doi.org/10.3390/su14031820.
46. Qazi, S., Khawaja, B.A. and Farooq, Q.U. (2022) 'IoT-equipped and AI-enabled next generation smart agriculture: A critical review, current challenges and future trends', *IEEE Access*, 10, pp. 21219–21235. Available at: https://doi.org/10.1109/ACCESS.2022.3152544.
47. Ramírez-Arroyo, A. et al. (2025) 'Multi-connectivity solutions for rural areas: Integrating terrestrial 5G and satellite networks to support innovative IoT use cases', *Smart Agricultural Technology*, 12, 101260. Available at: https://doi.org/10.1016/j.atech.2025.101260.
48. Rejeb, A. et al. (2022) 'The interplay between the Internet of Things and agriculture: A bibliometric analysis and research agenda', *Internet of Things*, 19, 100580. Available at: https://doi.org/10.1016/j.iot.2022.100580.
49. Rinaldi, F. et al. (2020) 'Non-terrestrial networks in 5G & beyond: A survey', *IEEE Access*, 8, pp. 165178–165200. Available at: https://doi.org/10.1109/ACCESS.2020.3022981.
50. Santika, T. et al. (2021) 'Impact of palm oil sustainability certification on village well-being and poverty in Indonesia', *Nature Sustainability*, 4, pp. 109–119. Available at: https://doi.org/10.1038/s41893-020-00630-1.
51. Shahab, H. et al. (2024) 'IoT-based agriculture management techniques for sustainable farming: A comprehensive review', *Computers and Electronics in Agriculture*, 220, 108851. Available at: https://doi.org/10.1016/j.compag.2024.108851.
52. Singh, A.K. et al. (2024) 'Smart connected farms and networked farmers to improve crop production, sustainability and profitability', *Frontiers in Agronomy*, 6, 1410829. Available at: https://doi.org/10.3389/fagro.2024.1410829.
53. Sinha, B.B. and Dhanalakshmi, R. (2022) 'Recent advancements and challenges of Internet of Things in smart agriculture: A survey', *Future Generation Computer Systems*, 126, pp. 169–184. Available at: https://doi.org/10.1016/j.future.2021.08.006.
54. Sugianto, H. et al. (2023) 'First things first: Widespread nutrient deficiencies limit yields in smallholder oil palm fields', *Agricultural Systems*, 210, 103709. Available at: https://doi.org/10.1016/j.agsy.2023.103709.
55. Sullivan, C.S. et al. (2024) 'Building trust: A systematic review of the drivers and barriers of agricultural data sharing', *Smart Agricultural Technology*, 8, 100477. Available at: https://doi.org/10.1016/j.atech.2024.100477.
56. Supriatna, J. et al. (2024) 'Sustainability analysis of smallholder oil palm plantations in several provinces in Indonesia', *Sustainability*, 16(11), 4383. Available at: https://doi.org/10.3390/su16114383.
57. Tang, Y. et al. (2021) 'A survey on the 5G network and its impact on agriculture: Challenges and opportunities', *Computers and Electronics in Agriculture*, 180, 105895. Available at: https://doi.org/10.1016/j.compag.2020.105895.
58. Tao, W. et al. (2021) 'Review of the Internet of Things communication technologies in smart agriculture and challenges', *Computers and Electronics in Agriculture*, 189, 106352. Available at: https://doi.org/10.1016/j.compag.2021.106352.
59. Watts, J.D. et al. (2021) 'Challenges faced by smallholders in achieving sustainable palm oil certification in Indonesia', *World Development*, 146, 105565. Available at: https://doi.org/10.1016/j.worlddev.2021.105565.
60. Wibowo, H., Sitanggang, I.S., Mushthofa and Adrianto, H.A. (2022) 'Large-scale oil palm trees detection from high-resolution remote sensing images using deep learning', *Big Data and Cognitive Computing*, 6(3), 89. Available at: https://doi.org/10.3390/bdcc6030089.
61. Wong, Y.B. et al. (2023) 'Smallholder oil palm plantation sustainability assessment using multi-criteria analysis and unmanned aerial vehicles',

Environmental Monitoring and Assessment, 195, 577. Available at: https://doi.org/10.1007/s10661-023-11113-z.

62. Xu, K. et al. (2021) 'A new machine learning approach in detecting the oil palm plantations using remote sensing data', *Remote Sensing*, 13(2), 236. Available at: https://doi.org/10.3390/rs13020236.
63. Xu, Y. et al. (2020) 'Annual oil palm plantation maps in Malaysia and Indonesia from 2001 to 2016', *Earth System Science Data*, 12, pp. 847–867. Available at: https://doi.org/10.5194/essd-12-847-2020.
64. Xu, Y. et al. (2022) 'Recent expansion of oil palm plantations into carbon-rich forests', *Nature Sustainability*, 5, pp. 574–577. Available at: https://doi.org/10.1038/s41893-022-00872-1.
65. Yang, X. et al. (2021) 'A survey on smart agriculture: Development modes, technologies, and security and privacy challenges', *IEEE/CAA Journal of Automatica Sinica*, 8(2), pp. 273–302. Available at: https://doi.org/10.1109/JAS.2020.1003536.
66. Zeng, J. et al. (2022) 'Optimization of open-access optical and radar satellite data in Google Earth Engine for oil palm mapping in the Muda River Basin, Malaysia', *Agriculture*, 12(9), 1435. Available at: https://doi.org/10.3390/agriculture12091435.
67. Zhao, J. et al. (2023) 'Replanting and yield increase strategies for alleviating the potential decline in palm oil production in Indonesia', *Agricultural Systems*, 210, 103714. Available at: https://doi.org/10.1016/j.agsy.2023.103714.