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Precision Agriculture for Smallholder Oil Palm Plantations: Barriers, Enabling Conditions, and Policy Pathways for Inclusive Digital Transformation

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ABSTRACT: Precision agriculture has increasingly been promoted as a pathway for improving productivity, input efficiency, environmental performance, and data-driven decision-making in perennial crop systems. In oil palm plantations, technologies such as remote sensing, unmanned aerial vehicles, machine learning, variable-rate fertilisation, digital farm records, and decision-support systems offer significant opportunities for yield improvement and sustainable intensification. However, the implementation of precision agriculture in smallholder-owned oil palm plantations remains constrained by multidimensional barriers. This article presents a qualitative literature review of recent scholarly works published mainly from 2020 onward to synthesise the technological, economic, institutional, infrastructural, agronomic, social, and policy-related challenges that shape smallholder adoption. The review argues that precision agriculture should not be understood merely as a technological package but as a socio-technical transformation requiring complementary assets, collective organization, trusted data governance, accessible finance, digital literacy, and supportive public policy. The findings indicate that individual smallholders often face high entry costs, limited plot-level data, fragmented landholdings, weak bargaining power, poor digital connectivity, and insufficient advisory services. Therefore, inclusive implementation requires phased adoption, cooperative-based service models, public–private–community partnerships, and integration with certification, traceability, and sustainable palm oil policy frameworks. The article concludes that smallholder precision agriculture can contribute to productivity, sustainability, and rural welfare only when technological innovation is embedded within institutional and policy ecosystems that reduce exclusion and distribute benefits fairly.

KEYWORDS: Precision Agriculture; Oil Palm; Smallholders; Digital Agriculture; Remote Sensing; Variable-Rate Fertilization; Technology Adoption; Sustainability Certification; Agricultural Policy; Inclusive Innovation.

1. INTRODUCTION

Oil palm is one of the most economically important perennial crops in the humid tropics. It contributes substantially to rural income, export earnings, food processing, oleochemical industries, and bioenergy supply in major producing countries such as Indonesia and Malaysia. Yet the sector is also associated with persistent sustainability debates, including land-use change, biodiversity loss, greenhouse gas emissions, peatland conversion, labour concerns, and uneven distribution of benefits across value-chain actors. Within this complex landscape, smallholder oil palm farmers occupy a strategic but vulnerable position. They contribute significantly to planted area and fresh fruit bunch supply, but their productivity, market access, technical capacity, and compliance readiness often lag behind those of large-scale estates and better-organised scheme farmers [1], [2], [3].

The productivity challenge is particularly important. Many smallholder plantations experience yield gaps caused by poor-quality seedlings, suboptimal fertilisation, limited soil and leaf analysis, inadequate harvesting intervals, ageing palms, weak drainage, lack of farm records, and insufficient access to agronomic advice. These limitations reduce household income and can indirectly increase pressure for land expansion. Sustainable intensification has therefore become a central policy and research concern: how can smallholder oil palm farmers increase productivity and profitability without expanding cultivation into forests, peatlands, or other ecologically sensitive areas? Precision agriculture offers one possible answer because it aims to improve farm management by applying the right input, at the right place, at the right time, and in the right amount [4], [5]. Precision agriculture refers to a set of data-driven management approaches that use spatial, temporal, and sensor-based information to support decision-making. Its technologies include remote sensing, drones, geographic information systems, soil sensors, weather stations, machine learning models, mobile applications, farm management information systems, and variable-rate input application. In oil palm, precision agriculture can support tree counting, plot mapping, yield prediction, nutrient management, pest and disease detection, replanting decisions, logistics planning, and sustainability monitoring [6], [7], [8], [9].

However, the promise of precision agriculture should not obscure its uneven accessibility. Much of the technology is designed for commercial farms that have larger areas, stronger capital, skilled staff, reliable data infrastructure, and established management systems. Smallholder farmers, by contrast, often cultivate small and fragmented plots, operate under tight cash-flow constraints, have limited access to credit, and rely on informal knowledge networks. They may not own smartphones with sufficient functionality, may live in areas with weak connectivity, and may have limited ability to interpret digital recommendations. Consequently, the adoption of precision agriculture among smallholders is not simply a matter of technological diffusion; it is a question of social inclusion, institutional design, affordability, trust, and policy support [10], [11], [12].

This article provides a qualitative literature review on the barriers and challenges of implementing precision agriculture in smallholder-owned oil palm plantations. Unlike a systematic literature review, this article does not seek to apply an exhaustive PRISMA-based screening protocol. Instead, it uses interpretive and thematic synthesis to bring together recent literature on precision agriculture, digital agriculture, smallholder technology adoption, oil palm sustainability, remote sensing, nutrient management, and policy intervention. The guiding assumption is that smallholder precision agriculture must be understood as a socio-technical system. Technologies alone cannot transform smallholder oil palm production unless they are connected to farmer organisations, financing mechanisms, extension systems, data governance, market incentives, and sustainability policy [13].

The article addresses five questions. First, what are the conceptual and technological foundations of precision agriculture relevant to oil palm plantations? Second, what benefits can precision agriculture provide for oil palm management? Third, what prerequisites are required for effective implementation? Fourth, what barriers are faced by smallholder oil palm farmers? Fifth, what strategies and policy interventions can enable smallholders to benefit from precision agriculture? By answering these questions, the article aims to contribute to academic and policy debates on inclusive digital transformation in tropical commodity systems.

2. LITERATURE REVIEW

2.1 Conceptual Foundations of Precision Agriculture

Precision agriculture emerged from the recognition that agricultural fields are not homogeneous. Soil fertility, slope, moisture, pest pressure, nutrient status, canopy condition, and yield potential vary across space and time. Conventional farm management often treats fields uniformly, applying the same fertiliser dosage, herbicide, or management schedule across large areas. Precision agriculture challenges this approach by using spatial data and analytical tools to identify variability and guide more targeted interventions [4], [14], [15].

In conceptual terms, precision agriculture overlaps with digital agriculture, smart farming, and Agriculture 4.0. Digital agriculture emphasises the use of digital tools across the agricultural value chain. Smart farming highlights automation, sensors, artificial intelligence, and real-time decision systems. Agriculture 4.0 refers to the broader integration of cyber-physical systems, big data, robotics, and platform technologies into farming. Precision agriculture is more specifically concerned with site-specific management and input optimisation. Yet in practice, these concepts increasingly intersect because precision farming depends on digital data, connectivity, and computational analytics [11], [16], [17], [18], [19], [20].

A key conceptual point is that precision agriculture is not merely a collection of tools. It is a management logic. A drone image, for example, becomes meaningful only when it is translated into an actionable decision: which palms require nutrient correction, which drainage blocks need repair, which areas show disease symptoms, or which parts of a plantation should be prioritised for replanting. Similarly, a digital farm map becomes valuable only when farmers, cooperatives, extension agents, or mills use it to improve planning, traceability, or service delivery. Therefore, precision agriculture should be interpreted as an integrated decision-support system rather than a stand-alone technology [21], [22].

Figure 1. Precision agriculture as a socio-technical system in smallholder oil palm plantations

Figure 1 illustrates that precision agriculture in smallholder oil palm plantations should be understood as a socio-technical system rather than a narrow technological package. Data collected from farms, drones, satellites, soil tests, and digital records only become useful when they are converted into practical decisions on fertilisation, harvesting, drainage, replanting, pest control, and certification compliance. The figure also emphasises that smallholders rarely adopt precision agriculture alone. Their capacity to benefit from digital tools depends on the surrounding ecosystem, including cooperatives, extension agents, mills, technology providers, financial institutions, and public agencies. Therefore, the success of precision agriculture in smallholder oil palm depends not only on technological accuracy but also on institutional coordination, farmer trust, affordability, and policy support [23], [24], [25].

2.2 Precision Agriculture Technologies Relevant to Oil Palm

Several technological domains are relevant to oil palm. First, remote sensing provides spatial information on plantation conditions. Satellite imagery can be used to map oil palm distribution, monitor canopy cover, classify industrial and smallholder plantations, and detect land-use change. High-resolution satellite products and machine learning classification have improved the ability to distinguish closed-canopy oil palm plantations from other land covers [1]. This is important for sustainability monitoring, smallholder mapping, and certification [26], [27], [28].

Second, unmanned aerial vehicles or drones offer higher-resolution imagery than many satellite products. Drones can support palm counting, stand inventory, canopy analysis, drainage assessment, and localised stress detection. In plantations with irregular planting patterns, missing palms, or mixed-age stands, drone imagery can help managers and farmer groups understand plot-level conditions more accurately. Deep learning approaches have demonstrated strong potential for large-scale oil palm tree detection from high-resolution imagery [6].

Third, machine learning can support yield prediction and crop monitoring. Oil palm yield is influenced by rainfall, temperature, soil moisture, solar radiation, palm age, fertilisation, management practices, and harvesting efficiency. Machine learning models can identify nonlinear relationships between environmental variables and fresh fruit bunch yield. Recent studies show that supervised learning and remote sensing-based models can improve yield estimation and support more timely plantation decisions [9], [29].

Fourth, precision nutrient management is particularly relevant because fertiliser is one of the largest cost components in oil palm production. Nutrient deficiencies reduce yield, but excessive or poorly timed fertilisation increases costs and can contribute to nutrient losses. Remote sensing, leaf nutrient analysis, soil testing, and variable-rate application can support more efficient fertiliser management. Research on variable-rate liquid fertiliser applicators for mature oil palm trees shows the technical feasibility of more targeted nutrient application, although the equipment and management capacity required may exceed what individual smallholders can afford [7].

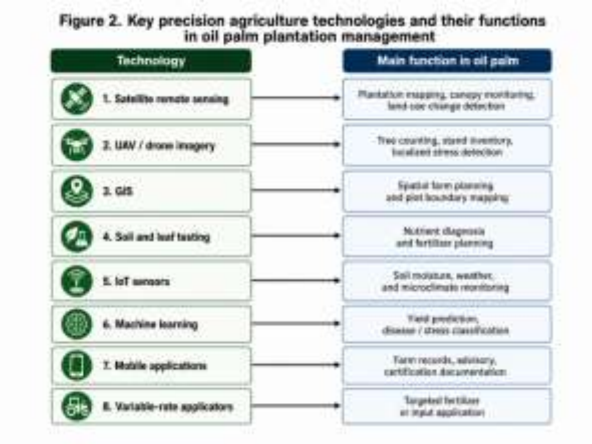

Figure 2. Key precision agriculture technologies and their functions in oil palm plantation management

Figure 2 summarises the main technological components of precision agriculture that are relevant to oil palm plantation management. The figure shows that each technology has a different function and level of complexity. Some tools, such as digital farm records, GPS-based plot mapping, and mobile advisory platforms, may be introduced at an early stage because they require relatively modest investment. Other technologies, such as UAV-based canopy analysis, machine learning prediction, and variable-rate fertiliser application, require stronger technical capacity and are more suitable for cooperative-based or service-provider models. This distinction is important because smallholder precision agriculture should be introduced progressively, beginning with low-cost and high-practicality tools before moving toward more advanced digital analytics and automation [24], [30], [31].

Fifth, digital platforms can support farm records, advisory services, certification documentation, traceability, and financial inclusion. Smallholders often lack accurate records on planting year, fertiliser use, yield, harvesting intervals, and farm boundaries. Digital record systems can improve farm planning and provide data required by certification schemes, mills, government agencies, or financial institutions. However, such systems must be designed to match smallholder realities, including language, usability, trust, connectivity, and data ownership concerns [10], [12].

2.3 Benefits of Precision Agriculture in Oil Palm

The first potential benefit is productivity improvement. Precision agriculture can help identify underperforming areas within smallholder plots. Some palms may suffer from nutrient deficiency, poor drainage, disease, pest attack, or ageing. Without spatial monitoring, these problems may remain hidden until yield losses become severe. Through plot mapping, canopy monitoring, and targeted advisory, farmers can allocate attention and inputs more effectively [6], [8].

The second benefit is input efficiency. Fertiliser is expensive, and smallholders often apply it based on generalised recommendations or available cash rather than actual nutrient needs. Precision nutrient management can help reduce under-application in deficient zones and over-application in areas where nutrients are sufficient. This improves both profitability and environmental performance. In large-scale plantations, evidence suggests that weed control and nutrient management practices can affect nutrient leaching and environmental outcomes, indicating the importance of better input targeting [32].

The third benefit is sustainability compliance. Certification schemes increasingly require documentation of farm boundaries, legality, good agricultural practices, environmental protection, and traceability. Digital mapping and farm records can help smallholders meet these requirements. Precision agriculture may therefore serve not only as a productivity tool but also as a compliance and market-access tool. This is important because independent smallholders often face greater difficulty than scheme smallholders in meeting certification standards [33], [34].

The fourth benefit is improved decision-making for replanting. Many smallholder plantations contain ageing palms, but replanting is costly because it temporarily reduces income. Precision data can help identify which blocks should be replanted first, estimate productivity decline, and support loan applications or government replanting programs. A more accurate farm inventory can reduce uncertainty and improve coordination between farmers, cooperatives, banks, and public agencies [3].

The fifth benefit is value-chain transparency. Palm oil supply chains face pressure from buyers, regulators, and civil society to demonstrate that production is legal, traceable, and deforestation-free. Digital mapping and traceability systems can help integrate smallholders into sustainable supply chains. However, this benefit will materialise only if smallholders are rewarded through better market access, technical services, or price incentives. Otherwise, digital traceability may become an additional compliance burden rather than a development opportunity [35], [36], [37].

2.4 Prerequisites for Effective Implementation

Several prerequisites are required for precision agriculture to work in smallholder oil palm contexts. The first is reliable plot-level data. Farmers need accurate information on land boundaries, palm age, planting density, yield history, soil condition, fertiliser application, and management practices. Without baseline data, precision agriculture recommendations may be inaccurate or too generic [26], [38], [39].

The second prerequisite is affordability. Smallholders are unlikely to purchase drones, sensors, advanced software, or variable-rate applicators individually. Therefore, access models matter. Cooperative-based services, pay-per-use drone mapping, shared soil testing, public extension platforms, and mill-supported advisory services may be more realistic than individual ownership [40], [41], [42].

The third prerequisite is human capacity. Digital tools require interpretation. A farmer may receive a nutrient map, but still needs practical advice on fertiliser type, dosage, timing, and application method. Precision agriculture must therefore be linked to extension services, farmer field schools, and local technicians. Capacity building should include both digital literacy and agronomic reasoning [11], [12].

The fourth prerequisite is rural infrastructure. Digital agriculture depends on electricity, mobile networks, internet connectivity, cloud systems, and device availability. In remote plantation areas, weak connectivity can limit real-time data transfer and platform use. Low-cost, offline-capable tools may be necessary for smallholders in such environments [43], [44], [45].

The fifth prerequisite is institutional trust. Farmers may worry that farm data will be used by companies, banks, government agencies, or buyers in ways that disadvantage them. Data collection can create fear of land control, exclusion from supply chains, taxation, or sanctions. Farmer-centric data governance is therefore essential. Farmers should know what data are collected, who controls them, how they are used, and what benefits they receive (Wiseman et al. 2021; Bronson 2022).

3. METHOD

This article uses a qualitative literature review design. A qualitative literature review is appropriate when the objective is to interpret, synthesise, and organise existing knowledge into meaningful themes rather than to measure effect sizes or exhaustively screen all available studies. It differs from a systematic literature review in several ways. A systematic review usually follows a predefined search protocol, inclusion and exclusion criteria, database strategy, screening procedure, and reporting framework such as PRISMA. A qualitative literature review is more flexible, interpretive, and conceptually oriented. It allows the researcher to combine theoretical, empirical, technical, and policy literature to develop a narrative synthesis [46], [47].

The literature reviewed for this article includes peer-reviewed journal articles, review papers, empirical studies, and technology-focused studies published mainly from 2020 onward. Older studies are used selectively where they provide foundational concepts or a widely cited background. The search focused on several themes: precision agriculture, digital agriculture, smart farming, Agriculture 4.0, smallholder technology adoption, oil palm remote sensing, oil palm yield prediction, nutrient management, sustainability certification, traceability, and agricultural policy.

The review followed an interpretive thematic process. First, literature on the conceptual foundations and technologies of precision agriculture was examined. Second, oil palm-specific studies were reviewed to identify relevant applications such as tree counting, nutrient classification, yield prediction, and plantation mapping. Third, smallholder digital agriculture and technology adoption studies were analysed to identify barriers and enabling conditions. Fourth, palm oil sustainability and certification literature were used to interpret the policy relevance of precision agriculture for smallholders. The evidence was then grouped into seven major themes: technological, economic, human-capital, infrastructural, agronomic, institutional, and market-related barriers [46].

This approach has limitations. Because it is not a systematic review, it does not claim exhaustive coverage. The selection of literature is interpretive and oriented toward conceptual synthesis. In addition, oil palm-specific research on precision agriculture for smallholders remains limited. Many technical studies focus on large plantations or experimental settings, while many smallholder studies focus on adoption barriers without directly examining precision agriculture. Therefore, the article synthesises both oil palm-specific and broader smallholder digital agriculture literature. This is justified because many adoption barriers are shared across smallholder contexts, even though oil palm has unique agronomic and value-chain characteristics.

4. RESULTS: THEMATIC FINDINGS

The thematic synthesis indicates that the barriers to precision agriculture adoption among smallholder oil palm farmers are not isolated or purely technical. Rather, they form an interconnected set of constraints involving technology design, investment capacity, digital and agronomic literacy, rural infrastructure, farm structure, institutional support, data governance, and value-chain incentives. As illustrated in Figure 3, these barriers interact around the central issue of smallholder precision agriculture adoption: expensive and complex technologies are difficult to use without adequate training; limited digital literacy reduces the usefulness of remote sensing and advisory platforms; poor connectivity constrains digital data flows; fragmented plots reduce economies of scale; weak cooperatives limit collective access to services; and insufficient market incentives reduce farmers' motivation to invest in new practices. This section, therefore, presents the findings thematically, beginning with technological barriers and then moving to economic, human-capital, infrastructural, agronomic, institutional, social, and market-related constraints that shape the feasibility of precision agriculture in smallholder-owned oil palm plantations [25], [48], [49], [50], [51].

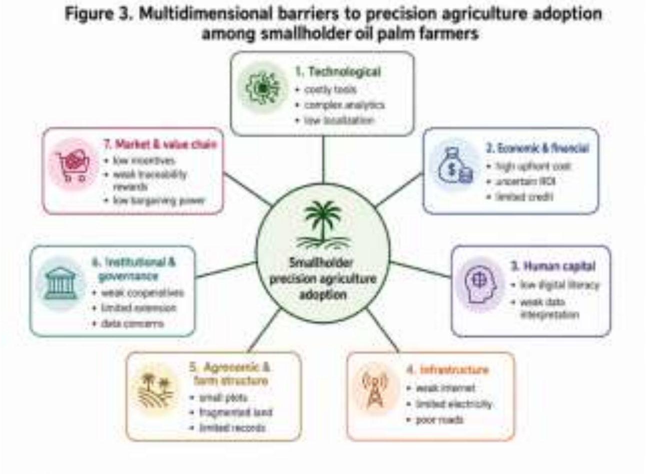

Figure 3. Multidimensional barriers to precision agriculture adoption among smallholder oil palm farmers

Figure 3 presents the thematic structure of the barriers identified in the literature. The figure highlights that the constraints faced by smallholder oil palm farmers are multidimensional and mutually reinforcing. High technology costs are closely linked to weak access to finance; limited digital literacy reduces the usefulness of advisory platforms; poor rural connectivity restricts data transmission; fragmented plots reduce economies of scale; and weak farmer organisations limit collective access to services. This means that precision agriculture adoption should not be analysed as a single technical decision. Instead, it should be examined as an outcome shaped by the interaction of technology, finance, knowledge, infrastructure, institutions, farm structure, and market incentives [23], [24], [52], [53], [54].

4.1 Technological Barriers

The first major barrier is technological mismatch. Precision agriculture tools are often designed for large farms or commercial estates where economies of scale justify investment in drones, sensors, software subscriptions, and specialised staff. Smallholder oil palm farmers generally manage smaller plots, often below the scale at which advanced technologies become individually profitable. Even when technologies are technically feasible, their design may not fit the operational realities of smallholder farms [4], [5], [25], [55].

A second technological barrier is complexity. Remote sensing maps, vegetation indices, machine learning outputs, and nutrient classifications are not automatically useful to farmers. They must be translated into simple, actionable recommendations. For example, a map indicating low canopy vigour is useful only if the farmer receives guidance on whether the problem is nutrient deficiency, water stress, disease, poor drainage, or ageing palms. Without interpretation, precision data can overwhelm rather than empower farmers [19], [56], [57].

A third barrier is a lack of interoperability. Smallholders may interact with multiple actors: cooperatives, mills, extension agents, banks, certification bodies, and government agencies. Each may use different data formats, platforms, or reporting requirements. Fragmented digital systems increase transaction costs and discourage adoption. Interoperability is particularly important if precision agriculture is expected to support traceability and certification [52], [58], [59], [60], [61].

A fourth technological barrier is insufficient localisation. Smallholder oil palm plantations vary in soil, slope, palm age, drainage, management history, and access to roads. Tools calibrated for large estates may not perform well in fragmented smallholder landscapes. Algorithms trained on commercial plantation imagery may misclassify smallholder plots with mixed vegetation, irregular planting patterns, or intercropping. Local validation is therefore necessary before digital recommendations can be trusted[62], [63], [64], [65].

4.2 Economic and Financial Barriers

Cost is one of the most frequently cited barriers to precision agriculture adoption. Drones, sensors, satellite analytics, software, soil testing, and advisory services require investment. Smallholders often operate with limited cash flow and may prioritise immediate household needs over uncertain technology investments. Even relatively low-cost digital tools may be unaffordable when farmers lack stable income or face volatile fresh fruit bunch prices [4], [15], [66].

Return on investment is also uncertain. Precision agriculture generates benefits over time, but smallholders may not clearly see how digital mapping or nutrient analysis will translate into higher income. If fertiliser prices are high, farmers may reduce application regardless of technical recommendations. If market prices are low, they may delay investment in technology. Adoption, therefore, depends not only on potential benefits but also on perceived risk and short-term liquidity [25], [67], [68], [69].

Access to finance is another challenge. Formal lenders may require land certificates, credit history, cooperative membership, or stable income records. Independent smallholders may lack such documentation. Ironically, precision agriculture could help produce farm records that improve creditworthiness, but farmers may need financing before they can adopt the tools that generate those records. This creates a circular constraint [70], [71], [72], [73].

Collective financing may reduce the burden. Cooperatives could purchase drone mapping services, organise soil testing, or employ digital extension workers on behalf of members. Mills or buyers could co-finance digital traceability if they benefit from more reliable supply-chain data. Government programs could subsidise early-stage adoption. Without such arrangements, precision agriculture may remain concentrated among larger and wealthier farmers [74], [75], [76].

4.3 Human Capital and Digital Literacy Barriers

Precision agriculture requires knowledge. Farmers need to understand why spatial variability matters, how data are collected, and how recommendations should be applied. Digital literacy is therefore central. Smallholders with limited education or limited smartphone experience may find digital applications difficult to use. Older farmers may rely more heavily on traditional experience, while younger household members may be more comfortable with mobile technologies [12], [49], [77].

However, digital literacy alone is insufficient. Agronomic literacy is also required. A farmer may know how to use a mobile application but still lack understanding of soil fertility, nutrient deficiency symptoms, fertiliser timing, palm physiology, or pest management. Precision agriculture, therefore, requires hybrid knowledge: digital skills combined with practical agronomy [78], [79], [80].

Extension services play a critical role, but many rural extension systems are under-resourced. One extension worker may be responsible for many villages or farmer groups. Extension agents may themselves lack training in remote sensing, digital records, or precision nutrient management. This creates a capacity gap between technological innovation and field-level implementation[81], [82], [83].

Peer learning can partially address this gap. Farmers are more likely to trust technologies when they see benefits demonstrated by neighbours or cooperative leaders. Demonstration plots, farmer field schools, and participatory mapping can make precision agriculture more tangible. Adoption should therefore be treated as a social learning process rather than a one-way technology transfer [84], [85], [86].

4.4 Infrastructure Barriers

Digital agriculture depends on infrastructure. Weak internet connectivity limits the use of cloud-based platforms, real-time advisory services, and digital traceability systems. Many smallholder oil palm areas are located in rural or frontier regions where mobile coverage is unstable. Even when coverage exists, data costs may discourage frequent use [87], [88], [89].

Electricity access also matters. Farmers need to charge smartphones, GPS devices, or tablets. Service providers need reliable power for data processing, drone batteries, and local offices. Poor roads can increase the cost of field visits, soil sampling, drone operations, and extension services. Infrastructure gaps, therefore, raise the transaction costs of precision agriculture[44], [90], [91].

Data infrastructure is equally important. Many smallholder plots are not formally mapped. Land boundaries may be unclear, overlapping, or informally recognised. Without reliable geospatial data, digital systems may reproduce or intensify land-tenure disputes. Mapping programs must therefore be linked to participatory validation and legal safeguards [92], [93], [94].

4.5 Agronomic and Farm-Structure Barriers

Smallholder oil palm plantations often have fragmented and heterogeneous structures. A household may own several small plots in different locations. Palms may have different ages because planting occurred gradually or because some palms were replaced after disease or mortality. Soil fertility may vary across short distances. Drainage may be uneven. These conditions increase the need for precision management but also make implementation more difficult [39], [95], [96].

Variable-rate technologies are easier to justify in large contiguous fields. In smallholder plots, the cost of collecting and analysing data may exceed the immediate economic benefit unless services are aggregated. For example, drone mapping becomes more affordable when conducted for an entire cooperative area rather than for one farmer's plot [97], [98], [99].

Farm records are often weak. Many smallholders do not systematically record fertiliser application, labour use, harvesting dates, or yield per plot. Without records, it is difficult to build predictive models or evaluate whether precision recommendations improve outcomes. Establishing basic digital farm records may therefore be the first stage of precision agriculture [4], [100], [101].

Ageing palms create another challenge. Precision agriculture can identify underperforming areas, but if the main cause is old palm age, the solution may be replanting rather than fertiliser adjustment. Replanting requires capital and temporary income support. Thus, precision data must be connected to broader farm investment planning [102], [103], [104].

4.6 Institutional and Governance Barriers

Institutional capacity strongly shapes adoption. Smallholders who belong to active cooperatives or farmer groups have better opportunities to access training, credit, certification, and collective services. Independent smallholders without strong organisations face greater difficulty. Precision agriculture is likely to be more feasible when delivered through collective institutions [105], [106].

Cooperatives can aggregate demand, reduce service costs, manage shared equipment, coordinate soil testing, maintain digital records, and negotiate with mills or technology providers. However, not all cooperatives are equally capable. Some lack managerial capacity, transparency, financial discipline, or member trust. Strengthening farmer organisations is therefore a prerequisite for inclusive precision agriculture [107], [108], [109].

Data governance is another institutional concern. Precision agriculture produces data about farm location, productivity, management practices, input use, and compliance status. These data can benefit farmers, but they can also shift power toward platforms, buyers, or state agencies. Farmers may be disadvantaged if they provide data without receiving services, price incentives, or control over how data are used. Farmer-centric data governance should include consent, transparency, benefit sharing, and grievance mechanisms [110], [111] .

Public policy coordination is also needed. Precision agriculture intersects with agriculture, digital infrastructure, land administration, rural finance, environmental regulation, and trade. Fragmented policy may produce overlapping platforms, inconsistent standards, and inefficient subsidies. Government should act as an ecosystem orchestrator rather than merely a technology promoter[68], [112], [113].

4.7 Social and Cultural Barriers

Trust is essential. Farmers may not adopt digital recommendations if they do not trust the source. They may question whether technology providers understand local conditions. They may suspect that mapping is intended to control land, impose sanctions, or exclude them from supply chains. This concern is especially relevant in palm oil because sustainability monitoring is closely linked to deforestation, legality, and certification [114], [115], [116], [117].

Traditional knowledge also matters. Smallholders often rely on experience, observation, and advice from neighbours or input sellers. Precision agriculture should not dismiss this knowledge. Instead, digital tools should complement the farmer experience. Participatory approaches can improve trust by allowing farmers to compare digital outputs with their own observations [117], [118], [119].

Social inequality may shape adoption. Better-off farmers, younger farmers, men, and cooperative members may adopt earlier, while poorer, older, female, or independent farmers may be excluded. Digital agriculture can therefore widen inequality if it is introduced without inclusive design. Policy must pay attention not only to average adoption rates but also to who benefits and who is left behind [120], [121], [122].

4.8 Market and Value-Chain Barriers

Precision agriculture adoption depends on incentives. If farmers do not receive higher prices, lower costs, better services, or improved market access, they may see little reason to adopt. Certification and traceability can create incentives, but smallholders often struggle to capture price premiums. Compliance requirements may increase paperwork and costs without guaranteeing better income [68], [123], [124].

Mills and buyers have an important role. They benefit from stable supply, quality improvement, traceability, and sustainability compliance. Therefore, they can support smallholder precision agriculture through advisory services, digital weighing systems, input credit, mapping, and cooperative partnerships. However, power asymmetry must be managed. Smallholders should not become data suppliers without fair benefits [125], [126], [127], [128].

Market integration is especially challenging for independent smallholders who sell through intermediaries. These farmers may not have direct relationships with mills, making it difficult to link farm-level data to market incentives. Strengthening smallholder–mill relationships is therefore important for precision agriculture implementation [129], [130], [131].

5. DISCUSSION AND ANALYSIS

5.1 Precision Agriculture as a Socio-Technical Transformation

The findings suggest that precision agriculture in smallholder oil palm plantations cannot be reduced to drones, sensors, or software. It is a socio-technical transformation that requires alignment between technology, institutions, finance, knowledge, infrastructure, and markets. A technically advanced tool can fail if farmers cannot afford it, do not understand it, distrust it, or cannot act on its recommendations. Conversely, even simple tools such as digital farm maps, mobile records, and soil testing can produce meaningful benefits when embedded in strong advisory and cooperative systems [23], [25], [89].

This perspective challenges technology-centric narratives. Many precision agriculture studies emphasise accuracy, algorithm performance, or technical feasibility. These contributions are important, but they do not automatically answer adoption questions. A deep learning model may detect oil palm trees accurately, but smallholders need to know how the output improves income, reduces cost, or helps them comply with certification. A nutrient map may classify deficiency, but farmers need affordable fertiliser, application guidance, and confidence that the recommendation is correct. Therefore, the social life of precision agriculture matters as much as the technology itself [25], [89], [132].

5.2 The Smallholder Adoption Paradox

The review identifies a smallholder adoption paradox. Smallholders may benefit greatly from precision agriculture because they often experience low productivity, inefficient input use, weak records, and limited market access. Yet they are also the least able to adopt precision agriculture individually because they lack capital, scale, data, skills, and institutional support. This paradox explains why market-led diffusion may be insufficient. If adoption depends only on individual purchasing power, precision agriculture will likely benefit larger farms first and widen the productivity gap [124], [133], [134].

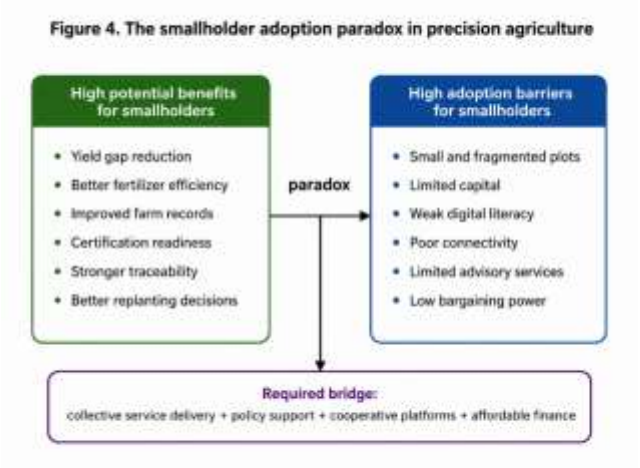

Figure 4. The smallholder adoption paradox in precision agriculture

Figure 4 explains the central paradox of precision agriculture in smallholder oil palm systems. Smallholders are among the actors who may benefit most from better data, targeted input use, farm mapping, and digital advisory services because many of them face persistent yield gaps and weak access to technical services. At the same time, they are also among the least prepared to adopt precision agriculture individually because they often lack capital, scale, digital skills, infrastructure, and institutional support. The figure, therefore, reinforces the argument that smallholder precision agriculture should not be promoted primarily through individual technology ownership. Instead, it should be enabled through collective service delivery, cooperative-based platforms, public subsidies, inclusive finance, and partnerships with mills, technology providers, and extension agencies [117], [135], [136].

The solution is not to abandon precision agriculture for smallholders, but to redesign its delivery model. Smallholders do not necessarily need to own every technology. They need access to useful information and services. A cooperative may contract drone mapping. A local extension center may provide soil testing and nutrient recommendations. A mill may support digital traceability. A public agency may subsidize farm mapping. A university may train local technicians. Such distributed service models can make precision agriculture accessible without requiring each farmer to become a technology owner. [25], [44], [137]

5.3 From High-Tech Adoption to Phased Adoption

For smallholder oil palm farmers, phased adoption is more realistic than full-scale precision agriculture. The first phase should focus on basic farm identity: plot mapping, farmer registration, palm age records, and yield recording. This creates the data foundation. The second phase can introduce soil and leaf testing, simple nutrient recommendations, and digital record keeping. The third phase can use remote sensing or drone imagery for canopy monitoring and stand inventory at a cooperative scale. The fourth phase can connect digital records to certification, traceability, credit, and market incentives [138], [139], [140].

This staged approach reduces risk. Farmers can see benefits gradually and build confidence. It also allows extension agents and cooperatives to develop capacity before managing more complex tools. A low-cost starting point is essential. Precision agriculture for smallholders should begin not with expensive equipment but with better information, better records, and better advisory services.

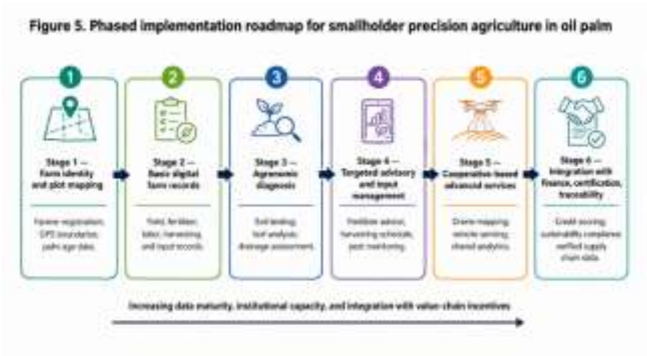
Figure 5. Phased implementation roadmap for smallholder precision agriculture in oil palm

Figure 5 proposes a phased roadmap for implementing precision agriculture in smallholder oil palm plantations. The roadmap begins with basic and foundational activities, such as plot mapping and farm record creation, because these steps generate the minimum data infrastructure required for more advanced precision services. Once basic records are available, farmers and cooperatives can gradually introduce soil testing, leaf analysis, targeted fertiliser recommendations, and digital advisory. More advanced tools, including drone mapping and remote sensing analytics, are best introduced at the cooperative or service-provider level to reduce costs and increase economies of scale. The final stage connects precision agriculture with finance, certification, and traceability, ensuring that digital transformation produces economic and institutional benefits for smallholders [136], [141], [142] .

5.4 Policy Pathways for Inclusive Implementation

Public policy has a central role in preventing digital exclusion. First, governments should support rural digital infrastructure. Connectivity is a public good that benefits agriculture, education, health, and rural enterprise. Without connectivity, digital agriculture will remain limited [143], [144], [145].

Second, governments should subsidise foundational precision services such as plot mapping, soil testing, farmer training, and digital farm records. These services produce public benefits by supporting sustainability, traceability, and land-use planning. Subsidies should be targeted toward smallholders, especially independent farmers and poorer households [25], [146], [147], [148].

Third, extension systems must be upgraded. Extension agents need training in digital tools, remote sensing interpretation, nutrient management, and data-driven advisory. Digital extension should not replace human extension. Instead, digital tools should strengthen extension agents by giving them better data and enabling more targeted advice [66], [149], [150].

Fourth, cooperative-based service units should be promoted. These units could provide drone mapping, soil sampling, digital record management, group training, and certification support. They could operate as local precision agriculture service hubs. Policy support may include grants, concessional loans, equipment-sharing programs, and technical partnerships with universities or start-ups [151], [152], [153].

Fifth, agricultural finance should be linked to precision agriculture. Banks and public finance institutions can use digital farm records to assess creditworthiness, while loans can support fertiliser, replanting, or technology services. Credit guarantees may reduce lender risk. However, data use must be fair and transparent [126], [154], [155].

Sixth, precision agriculture should be integrated with sustainability certification and traceability. Certification schemes such as ISPO, MSPO, and RSPO require data. Digital tools can reduce documentation burdens, but farmers should receive tangible benefits. Policy should encourage buyers and mills to reward verified sustainable production through market access, services, or premiums [36], [52], [156].

Seventh, farmers' data rights should be protected. Policies should clarify ownership, access, consent, data sharing, and benefit distribution. Smallholders must not be reduced to passive data providers. Data governance should empower farmers and strengthen their bargaining position[157], [158], [159] .

Figure 6. Policy and institutional ecosystem for inclusive precision agriculture adoption

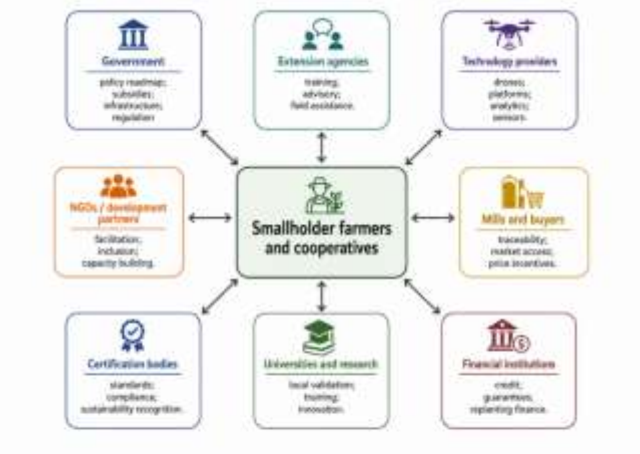

Figure 6 presents the institutional ecosystem required to support inclusive precision agriculture adoption among smallholder oil palm farmers. The figure shows that smallholders and cooperatives should be positioned at the centre of the ecosystem, while other actors provide complementary resources. Government agencies can create enabling policies, infrastructure, and targeted subsidies. Extension agencies can translate digital information into practical agronomic advice. Technology providers can offer affordable and locally adapted tools. Mills and buyers can create market incentives by linking digital traceability with preferential sourcing or sustainability rewards. Financial institutions can reduce adoption barriers through credit and guarantees, while universities, certification bodies, and development partners can support validation, training, and institutional trust. The figure reinforces the argument that precision agriculture becomes inclusive only when innovation is supported by coordinated policy and institutional arrangements [13], [160], [161], [162], [163], [164], [165].

5.5 Toward a Holistic Implementation Model

A holistic implementation model for smallholder oil palm precision agriculture should include six components. The first is farmer-centred design. Tools must be simple, local-language, offline-capable, and aligned with everyday farming decisions. The second is collective delivery. Cooperatives, farmer groups, and village institutions should aggregate demand and reduce service costs. The third is integrated advisory. Digital outputs must be translated into agronomic recommendations. The fourth is financial inclusion. Smallholders need credit, subsidies, insurance, or pay-per-use models. The fifth is market linkage. Precision agriculture should improve access to mills, certification, and traceable supply chains. The sixth is data justice. Farmers should control and benefit from their data [80], [142], [166], [167], [168].

This model shifts the focus from adoption as an individual decision to adoption as an ecosystem outcome. Farmers adopt when the surrounding ecosystem makes adoption useful, affordable, trustworthy, and rewarding. Therefore, inclusive precision agriculture requires coordination among government, cooperatives, mills, technology providers, banks, universities, NGOs, and certification bodies.

6. CONCLUSION

Precision agriculture offers substantial potential for improving productivity, input efficiency, environmental performance, and sustainability compliance in oil palm plantations. Technologies such as remote sensing, drones, machine learning, digital farm records, nutrient mapping, and variable-rate fertilisation can support better decisions at plot, cooperative, and supply-chain levels. For smallholder oil palm farmers, these tools may help close yield gaps, reduce input waste, improve replanting decisions, strengthen traceability, and support certification readiness.

However, implementation in smallholder-owned plantations faces multidimensional barriers. These include high technology costs, uncertain returns, limited access to finance, weak digital literacy, poor connectivity, fragmented landholdings, inadequate farm records, limited extension capacity, weak cooperatives, unclear data governance, and insufficient market incentives. These barriers show that precision agriculture is not merely a technical challenge. It is a socio-technical and institutional challenge.

The main conclusion is that smallholder precision agriculture must be designed as an inclusive ecosystem. Individual ownership of advanced technologies is not the most realistic pathway. Instead, smallholders require access to shared services, cooperative-based platforms, public extension support, affordable finance, trusted data systems, and market rewards. Phased adoption is essential: start with plot mapping and farm records, then introduce soil and leaf testing, targeted fertilisation, drone or satellite monitoring, and finally integration with certification, traceability, and finance.

Policy recommendations include developing national and regional smallholder precision agriculture roadmaps, establishing cooperative-based service units, subsidising foundational digital and agronomic services, upgrading extension capacity, improving rural connectivity, creating blended finance mechanisms, integrating precision agriculture with sustainability certification, and protecting farmer data rights. With these interventions, precision agriculture can become more than a tool for plantation modernisation. It can become a pathway for inclusive rural transformation, sustainable intensification, and fairer participation of smallholder farmers in the palm oil economy.

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