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PRECISION AGRICULTURE IMPLEMENTATION TO IMPROVE SUSTAINABILITY AND PRODUCTIVITY OF OIL PALM PLANTATIONS IN INDONESIA: A REVIEW

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ABSTRACT

Oil palm plantations have emerged as a strategic catalyst for Indonesian economic growth, with planted areas expanding by 71% from 2010 to 2020. The expansion of cultivated regions contributes significantly to state revenue and attracts domestic and international criticism. Two major issues are associated with oil palm plantations in Indonesia: (1) The adverse consequences of land conversion and (2) the limited productivity of these plantations. The conversion of land, mainly deforestation and peatland transformation, is widely believed to be responsible for biodiversity depletion and a substantial surge in greenhouse gas emissions. However, many oil palm plantations in Indonesia suffer from poor productivity, making such sustainability ventures questionable. Over the years, the application of Precision Agriculture (PA) techniques has demonstrated their effectiveness in minimising agricultural inputs, optimising yields and mitigating environmental impacts. This article explores how PA practices can elevate oil palm plantation productivity and ensure sustainability through dependable field monitoring systems, adept database management, transparency and traceability, site-specific agriculture and a robust decision support system. The article will also delve into the challenges faced by smallholder farmers who require support to adopt PA due to high initial investment, socio-cultural resistance and limited capacity for embracing new technology.

Keywords: ISPO, oil palm plantations, precision agriculture, RSPO, sustainability.

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INTRODUCTION

Indonesia, one of the most significant crude palm oil (CPO) producers, produced 44.76 million tonnes in 2020. About 61.7% of the production was exported worldwide, generating state revenue of 18.69 billion dollars. This massive production came from plantation areas of 14.59 million hectares spread throughout the country (Badan Pusat Statistik [BPS] Indonesia, 2021), suggesting land productivity is around 3.1 t of CPO ha^{-1}. Malaysia had a land productivity of 3.2 t of CPO ha^{-1} in the same year after producing 19.14 million tonnes of CPO from planted areas of 5.87 million hectares (Parveez et al., 2021). The most updated data cannot be interpreted further since the COVID-19 pandemic of 2020-2022. The pandemic has disrupted the supply and demand of CPO and made the prices uncertain. The CPO price volatility continued the following year after the pandemic (Gandhy et al., 2022). However, in the previous study based on the data released by BPS Indonesia (2017) and Malaysian Palm Oil Board (MPOB, 2017), Indonesian palm oil (productivity per hactare) falls constantly below Malaysia's

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productivity level. Malaysia reached an average productivity of 4.28 t CPO ha^{-1}, while Indonesia reached 3.41 t CPO ha^{-1} from 2000 to 2015. Malaysia has already achieved more than 4 t ha^{-1}, while Indonesia only achieved the best productivity of 3.68 in 2015 (Hudori, 2017). Increasing productivity and sustainability is a challenge for the Indonesian oil palm industry. *Vice versa*, in the late 1990s, Malaysia committed to preserving a minimum of 50% forest cover, consequently leading the Malaysian oil palm industry to prioritise intensification within their territory. Indeed, Malaysian investors have continued to enlarge their oil palm cultivation areas within Indonesian land.

Besides the land productivity issue, the environmental issue of oil palm plantations in Indonesia has long been in the spotlight. The heightened environmental concerns have come from the European Union (EU), one of the biggest importers of CPO. Despite efforts made by palm oil-producing countries to ensure the sustainability of their palm oil, the EU insists that it is hard to establish sustainability in the oil palm industry. The EU has even committed to reducing palm oil use and will stop using it for biofuel in 2030. One of the criticisms of the palm oil industry is that oil palm plantation is an incredibly destructive and malicious form of agriculture due to massive expansion. The expansion, especially in forests and peatlands, causes more CO_2 emissions and biodiversity losses. Sustainable palm oil management can be achieved by intensifying, rather than expanding, land tenure security with vital forest conservation and better support for smallholders for a fair negotiation (Idriyadi, 2022). Based on data from Statistic Indonesia, the planted area has increased by 71% over 10 years, from 8.55 million hectares in 2010 to 14.59 million hectares in 2020 (BPS Indonesia, 2017, 2021). The transformation of forests and peatlands into oil palm plantations has been identified as a significant contributor to greenhouse gas (GHG) emissions, accounting for 15%–25% of Indonesia's total carbon emissions. The previous research concluded that the land cover changes to commercial oil palm plantations are responsible for the increase in total carbon emissions in Indonesia, especially on the islands of Sumatra and Kalimantan, leading to Indonesia being placed among the ten biggest carbon emitters (Shahputra & Zen, 2018).

Productivity and sustainability should not be seen as conflicting goals for oil palm plantations. In agroecological practices, productivity can be an indicator of agroecosystem sustainability. Reducing input consumption (e.g., water, pesticides, fertiliser) can ease the environmental burden. Hence, it enhances efficiency, boosts productivity, and reinforces sustainability (Wezel et al., 2014). The article discourse revolves around this concept. This article considers sustainability based on Indonesia Sustainable Palm Oil (ISPO) and Roundtable Sustainable Palm Oil (RSPO) in the discussion since these two certifications have been recognised and applied in Indonesia. The Indonesian Government has implemented ISPO to promote sustainability. However, a perspective emerges that the ISPO standard holds complexities, aiming to reassert national governance authority and accommodate the domestic palm oil sector, all the while assimilating norms advocated by international private governance. Conversely, some contend that ISPO serves as a counterbalance to RSPO, alleviating foreign pressures on the oil palm industry by positioning it as a domestic enterprise. Although there is a gap between ISPO and RSPO, both have the understanding to minimise the adverse effects with different emphases on their side (Choiruzzad et al., 2021).

The focus of the discussion is the possibility of adopting Precision Agriculture (PA) practices in Indonesian oil palm plantations to achieve better productivity and sustainability through increasing compliance with ISPO and RSPO principles. PA is a management strategy that gathers, processes and analyses temporal, spatial and individual plant and animal data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production (International Society of Precision Agriculture [ISPA], 2024). PA has characteristics as an integrated and production-oriented farming system aimed at improving long-term, site-specific and whole farming production, typically in productivity, efficiency, and profitability, while simultaneously minimising unwanted impacts on the environment and wildlife (Joint Research Centre, 2014). PA is practised in the oil palm industry, particularly in crop, water, and soil management (Tan et al., 2022). However, implementing all existing technologies must follow the conditions under which they are applied. So, this article also discusses the challenges that exist in Indonesia in implementing PA. The discussion in the article takes a technocentric and ecocentric perspective, especially regarding how to improve land productivity and sustainability because the oil palm industry has many intersecting and broadsides. The principles of RSPO and ISPO discussed in this article represent an ecocentric perspective which is the core of sustainability. Technocentric focuses more on technology and science as a way to repair the damage done to the environment rather than changing the ethical perspectives on environmental issues (Salman, 2019). This discussion aims to provide new insights into PA applications in oil palm plantations in Indonesia.

MATERIALS AND METHODS

The scope of this article varies based on the differences in the oil palm plantations in Indonesia, which comprise large companies, smallholders, or state plantations. This review article is focused to draw the formulation around two focal themes: Low productivity and low adherence to sustainability principles in managing oil palm plantations in Indonesia. The discussion in this article started with the understanding that increasing productivity results from maintaining sustainability. Sustainability standard in Indonesia refers to ISPO and RSPO, so the discussion starts with how ISPO and RSPO are positioned in Indonesia's oil palm industry. By understanding the gap between the implementation of ISPO and RSPO conducted in Indonesia and the standards that must be achieved, it is hoped that there will be an overview of areas that can be improved through applying PA to increase compliance with sustainability principles.

The authors reviewed several journal articles, proceedings and conferences to determine the implementation of ISPO and RSPO in Indonesia, the challenges to increasing adherence to sustainability principles and the possibility of implementing PA in Indonesian oil palm plantations. Utilisation of search engines like Scopus, PubMed, IEEE Explore and Google Scholar are used to explore previous publications related to the topic discussion. The primary statistical data used in this article are taken from annual reports issued by Statistics Indonesia. Work report from related Indonesian ministries and leading non-governmental organisations (NGOs) are also used as a reference for the latest data on the development of Indonesian oil palm plantations. The authors also reviewed some previous research about the application of PA and discussed the possibility of implementing PA by considering the existing conditions in Indonesia.

RESULTS AND DISCUSSION

Sustainability Through RSPO and ISPO

Defining the gap and similarity between RSPO and ISPO is a base to identify the essential steps to improve adherence to sustainability principles, and in the end, can improve productivity. Sustainability and productivity are linked in one direction. Sustainability practices such as enhancing agroecosystem balance through agroecological practices are proven to generate high palm oil yields (Bessou et al., 2017). On a broader understanding, sustainability increases fresh fruit bunches (FFB) production and gives social, economic, and environmental benefits (Nurliza et al., 2022). ISPO is a certification launched by the Indonesian Ministry of Agriculture that is mandatory for oil palm plantation companies, plantations with no mills, and mills without plantations (Hutabarat, 2018).

TABLE 1. DIFFERENCES BETWEEN ISPO AND RSPO

Item	ISPO	RSPO
Source of regulations	Regulation of the Minister of Agriculture of the Republic of Indonesia regulation No. 38 of 2020.	Implemented based on RSPO principles and criteria 2018.
Regulatory entanglement	Mandatory in 2025.	Voluntary.
Principles	• Compliance with laws and regulations. • Implementation of good agriculture practices (GAP). • Good management of the environment, natural resources and biodiversity. • Implementation of sustainable business transparency.	• Legality of respect for land rights and community welfare. • Optimise productivity, positive impacts and resilience. • Protect, conserve and enhance ecosystems and the environment. • Respect for human rights, including labour rights and working conditions.
The land used	Oil palm land development must be legally sound and its location refers to the spatial planning determined by the Indonesian government.	No new plantings in areas of high conservation value in forests with high carbon stock, in areas with steep slopes of more than 22°, in peat areas and in the regions that do not have free, prior and informed consent (FPIC) from indigenous peoples, local communities, or other users.
Focus and recognition	ISPO focuses more on business legality and compliance with Indonesian laws and regulations. Its certificates are valid nationally.	More concerned with realising a sustainable oil palm plantation business and its certification applies internationally.
First audit	ISPO certification bodies must conduct a first-phase audit within three months of signing the ISPO certification agreement.	The first audit is conducted after becoming an RSPO member and implementing the RSPO principles and criteria and has prepared for the first audit.
Conservation area	At least 30% of the area is designated as conservation area.	Requires 75% protection for areas classified as high conservation value (HCV) and a minimum of 35% designated as conservation areas.

In contrast, RSPO is a non-governmental certification programme founded by multi-stakeholder groups, including representatives from the private sector, NGOs and investors, that promote sustainable oil palm production (Apriani et al., 2020). The party supporting RSPO argues that ISPO is the way for the government to protect its industry by adopting environmental values as a trading tool. The other party that rejected RSPO insists that RSPO is the tool from the West to regulate domestic and strive to transcend nation sovereignty (Choiruzzad et al., 2021). This divergent viewpoint has frequently been attributed to the perception that sustainability principles in the oil palm industry can be disputed and disobeyed by the stakeholders, even though both standards fundamentally aim to uphold environmental and social responsibility.

The differences between ISPO and RSPO are primarily in the criteria for high conservation values (HCV), free prior and informed consent (FPIC), peatland and new planting procedures (NPP). RSPO is more stringent in tying commitment, and demands more transparency and more detailed mandatory steps, especially concerning environmental and social impact. For example, in using peat as a planted area, RSPO encourages making a voluntary commitment to avoid peatlands and demands the implementation of best management practices (BMPs) for peatland management. However, the previous ISPO regulations still permit peatland cultivation under specific conditions, demanding the prevention of negative repercussions and preserving water levels within defined parameters. The specified conditions that would enable peat to be planted are peat areas constituting less than 70% of the concession area, with depths of less than 3 m (EFECA, 2018). RSPO has more comprehensive details and requirements than ISPO, particularly on indicators of labelling, trust, fair treatment for smallholders, smallholder credit, farmer market access and conflict resolution (Wulandari & Nasution, 2021). There is even an assumption that RSPO emphasises sustainable oil palm plantation practices to reduce deforestation and protect biodiversity. In contrast, ISPO is the state initiative to raise global market competitiveness by paying attention to environmental challenges and commitment to GHG emissions (Sylvia et al., 2022).

RSPO and ISPO impel the stakeholders to maintain sustainability. The principles of ISPO overlap with those of RSPO, encompassing aspects like legal compliance, environmental stewardship, social accountability and sound business ethics (Hutabarat, 2018). Both certifications aim to encourage palm oil production by considering economic, environmental and social pillars. Also, both demand compliance with laws and regulations, good management practices for sustainable plantations, environmental responsibility, sensitivity to the needs of workers and communities and continuous improvement (Widiati et al., 2020). The journey toward ISPO and RSPO implementation is also always dynamic, primarily to accommodate smallholder farmers. The RSPO sets a standard acceptable to oil palm smallholders in Indonesia. The RSPO implementation flow should be as simple as possible to relieve barriers to smallholders. An example is the relaxation to address the GHG effects, social impact assessment, and the burden caused by the administrative system to assist smallholders in complying with the principles and criteria of RSPO (Sylvia et al., 2022). Simultaneously, the revised ISPO has integrated the principle of transparency as an evaluative factor, though concerns persist regarding its effective execution. ISPO also implements less stringent conditions for smallholders by excluding principle requirements of responsibilities towards workers' rights, social responsibilities, and community economic empowerment (Barahamin et al., 2022).

Indonesia is committed to strengthening the implementation of ISPO since the compliance rate is still low. According to the Head of Plantation Service for Riau Province, only 30.00% of the oil palm companies have fulfilled ISPO certification in Riau until 2022 (Wulandari & Nasution, 2021). Moreover, only 37.00% of the oil palm industries in the country received ISPO certification in 2019. The most frequent obstacles to increasing ISPO compliances are legality issues of land use rights and lack of global market stimulus. The legality issues are prevalent among smallholder oil palm holdings. Many of these holdings are being established in areas not included in the spatial plan (Sylvia et al., 2022). The obligation to get ISPO certification was strengthened by Indonesian Presidential Regulation No. 44 of 2020, which aimed to improve ISPO compliance (JDIH BPK, 2020). The obligation encourages all oil palm industry players to obtain ISPO certification no later than five years after the issuance of this Presidential Regulation (Badan Standardisasi Nasional [BSN] Indonesia, 2020). Another challenge after issuing Presidential Regulation No. 44 of 2020 is to ensure transparency. It will force the palm oil mills to refuse FFB from smallholders or plasma plantations that are not ISPO-certified because only 0.21% of plasma plantations were certified in 2019. The plasma plantations face a great challenge in fulfilling the requirement of land legality and origin of seeds certification as a prerequisite of transparency. The application of certified seeds by smallholder farmers is still low. The use of forests illegally due to weak oversight makes it difficult to clarify land legality. This condition will be more challenging since many smallholders or plasma plantations need to understand the principles of environmental management that meet ISPO standards (Purwanto, 2020). The plantations owned by big corporations also have not yet fully implemented ISPO principles, especially the third principle. Based on assessing five oil palm plantation companies in East Kalimantan Province, implementing the environmental management and monitoring the 3rd principle could only reach the average achievement level of 54.69% (Anwar et al., 2016).

In order to fulfil the Paris Agreement, the implementation of ISPO and RSPO will be necessary in Indonesia. One of the objectives of this agreement is to reduce GHG emissions with a reduction target of 29% and up to 41% compared to business as usual in 2030 (Ministry of Environment and Forestry Republic of Indonesia, 2022). The commitment to reduce GHG obliged the Indonesian Government to evaluate the policies to prioritise conservation rather than expansion, significantly reducing peatland cultivation (Maskun et al., 2021). Indonesia's commitment can be seen in the latest ISPO changes published in 2020. There is a more robust requirements indicator pointing to a ban on peatland use. The new ISPO does not permit new planting on peatland, regardless of depth, after 15 November 2018, in existing plantation areas and new development areas (Kehati et al., 2021). The strong commitment from the central Government should drive regional regulators and plantation management to improve agriculture practices. Some practices in the field can support the GHG reduction commitment like reducing land clearing in areas with high carbon content, conducting soil and water conservation, utilising no over-fertilising, promoting the use of empty fruit bunches (EFB) for fertilisation, controlling the use of pesticides and practising good water level management for peat areas (Sylvia et al., 2022).

Increasing Productivity by Maintaining Sustainability

The critical step to maintaining sustainability and reducing GHG emissions is to slow down the expansion of land use conversion, particularly on the conversion of forests and peats and Indonesia has taken policies such as a permanent extension of the forest and peatland moratoriums based on Presidential Instruction No. 5 of 2019 (United Nations Framework Convention on Climate Change [UNFCC] , 2021). This new policy direction demanded that the plantation be more able to intensify and improve land productivity. Smallholdings or plasma plantations with financial, knowledge and supply chain barriers face low productivity problems. Insufficient availability of certified seeds and adequate fertiliser hinders smallholders aiming to enhance productivity (Herdiansyah et al., 2020). Efforts to maintain the balance of nature by paying attention to sustainability principles can have a strong impact on the productivity of oil palm plantations in the long term as shown in *Figure 1*.

Smallholdings face greater vulnerability to low productivity issues. Expanding the cultivated area yields more detrimental outcomes than benefits. Larger planted areas necessitate increased

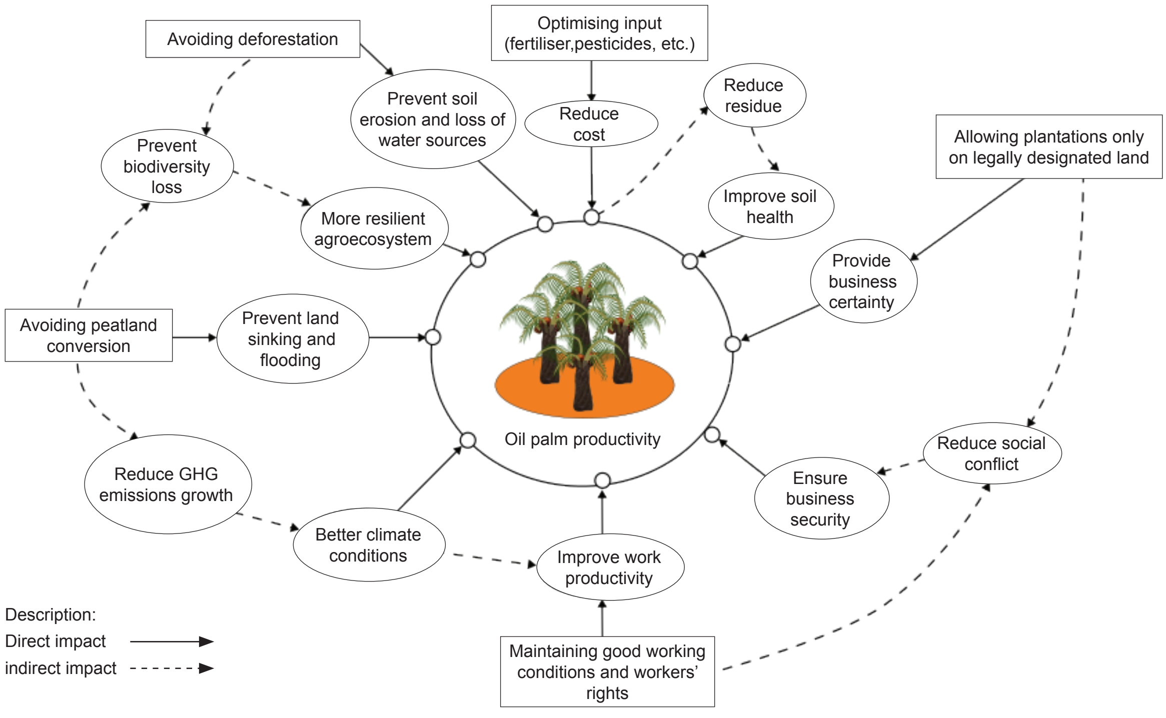

Figure 1. Illustration of operations that consider sustainability can affect palm oil productivity.

quantities of oil palm trees, ultimately demanding higher fertiliser and labour inputs, despite yielding below-expectation due to these adverse effects. Since deforestation triggers ecosystem imbalance, it needs more resources to handle the impacts such as the spread of plant pests and diseases, land degradation and loss of water resources. Based on the research conducted by Sari et al. (2021), ecosystem imbalance causes the effort to control pests to be higher than fertilisation and reduces the yield of the oil palm tree. Hence, all the significant factors in palm oil production, such as land maintenance, fertiliser and pesticides, must be maintained more efficiently (Yanita & Suandi, 2021).

Trade-offs and mutualism always exist among ecosystem services in an agroecosystem. Good agriculture management practices can reduce losses among ecosystem services and maximise the provisioning among ecosystem services (Power, 2010). The conversion of land use and land cover is an appropriate example of the dynamics of trade-offs and mutualism among ecosystem services. The relationship of the ecosystems is complex, but at least, based on ecological footprint examination, two opposing processes can be determined. The first process is the biological capacity of the agroecosystem to produce needs and absorb the by-products, and the second is the demand for agroecosystem services by a group population. Deeper comprehension can be explored through an integrated model considering economic, geographic and ecological issues to capture multiple drivers of changing land use and cover (United Nations Department of Economic and Social Affairs [UN-DESA], 2012). High demand for palm oil products was reported as the main driver in Indonesia and Malaysia's conversion of land use and land cover. To attain sustainability, opting for best management practices offers a more effective route to increasing oil palm yield than converting new land for cultivation (Wicke et al., 2011). The best management practice in oil palm plantations covers many areas, including agronomy, soil-water management, financial management, harvesting and transportation, people management, and innovation (Pardamean, 2017). Best management practices could reduce pressure to convert up to 1.6 million hectares of land to new plantations by 2050. Crop recovery, canopy management and soil, moisture and nutrient management are the backbone of best practice management implementation (Paoli et al., 2014).

The productivity of FFB and CPO is also contingent upon land suitability and the implementation of technical cultivation practices. Land suitability is classified based on soil types, rainfall and soil content. The technical cultivation standard adheres to the principles of good agricultural practices. Enforcing these technical cultivation practices entails employing well-suited land, quality seeding, appropriate fertilisation, meticulous maintenance and effective harvesting techniques (Anwar et al., 2014). Furthermore, pests and disease control must be considered. The technical cultivation standard also encompasses specific targets to accomplish, including the quantity of prenursery seeds that experience delayed transfer to the main nursery, the count of unripe FFB harvested and the frequency of harvesting rounds (Suryani et al., 2019). The study on production enhancement carried out by Hidayati et al. (2014) has definitively established a hierarchy of priority factors for boosting productivity, listed from the highest to the lowest level: Plant health, reseeding, fertiliser type, fertiliser dosage, suitability of tools and working materials, soil type, frequency of fertiliser application, work procedures, weed control, pest management, fertiliser technology and seed fertilisation. The oil palm tree population and uniformity are significant factors in improving productivity. Good plant health, especially in nursery and planting, will minimise reseeding and ultimately, suppress heterogeneity. The reseeding is replanting activities due to plant seed failure to grow and is done to ensure a fixed number of trees and low variation of different planting years per planting area. The uniformity of tree crops creates a better set up to apply the same treatment in nutrient application fertilisation, weed, and pest control. The nutrient application is also necessary to improve palm oil production per hectare. Fertiliser type, amount and application method have significant effects on productivity.

Precision Farming for Maintaining Sustainability and Improving Productivity

The Indonesian Government has shown commitment to sustainability and has proven it by implementing new ISPO to increase palm oil sustainability and productivity. The Government understands that low crop productivity rates, high production cost, low practical awareness of sustainability, land legality and suitability are challenges to the improvement of oil palm plantations, be more competitive and hence sustainable for the industry in Indonesia (Ministry of Industry of the Republic of Indonesia, 2021). However, the implementation of the Government's commitment is still doubtful. Furthermore, the problems that become critical and significant challenges are weak supervision and poor law enforcement against illegal practices, so many oil palm plantations are being established inside unspecified areas. This situation makes it challenging to enforce land legality as required by ISPO and RSPO (Santoso & Saputra, 2020). Based on the shortcomings described above, the barriers faced in upholding the sustainability principles in the oil palm industry can be determined by several factors. These factors are weak supervision, both for illegal land use changes or wrong plantation operations that damage the environment; low continuous improvement system; lack of transparency and traceability implementation to ensure sustainability; the difficulty of applying best management practices and good agricultural practices; and inaccurate policy making directions, both from regional government or strategy policy from the plantation management. These barriers need to be overcome, and PA is an option to overcome them.

PA can be defined as improving crop yields and assisting management decisions using high-technology sensors and analytical tools (Singh et al., 2020). PA can assist good agricultural practices or best management practices in the oil palm cultivation business (Tan et al., 2022). PA tools and techniques include but are not limited to, variable rate technology, soil mapping, remote sensing technology, unmanned aerial vehicles (UAV), tractor guidance systems and monitoring and mapping yield (Mcconnell, 2019). Based on the five barrier sectors mentioned above that challenge the enhancement of sustainability and productivity of oil palm plantations in Indonesia, five parameters of PA applications can be proposed. The proposed five parameters of PA applications appear in *Table 2*, consisting of reliable field monitoring systems, database management systems, transparency and traceability systems, site-specific agriculture and a decision support system.

Reliable Field Monitoring System

The authority in Indonesia has implemented coordination, control and surveillance to prevent deforestation. However, it should be strengthened because oil palm canopy cover remains in the middle of a protected forest (Nughara, 2019). Although the Central Government has already imposed a moratorium on new land clearing from virgin forest and peatland to oil palm plantations, deforestation and peatland fires are caused by many factors, including poor supervision and control (Drost et al., 2021). Immediate and accurate monitoring in the field is vital to control and supervise land use. Reliable methods are necessary to recognise, detect, monitor, analyse and predict. The adoption of technologies such as GPS, GIS, UAVs and satellites for remote sensing has already been set up to monitor land cover changes. Even aerial photographs have been used to map land cover and land use since the 1940s (Wavan et al., 2006). An example is satellite imagery used for the estimation of leaf nitrogen content based on Sentinel 1-A imagery. The estimation accuracy is quite high using a random forest regression model. The estimation results can be used for planning, monitoring and providing fertiliser recommendations (Munir et al., 2023). PA implementation can help monitor soil conditions, land suitability and feedback from communities living around the plantation in real-time as shown in *Figure 2*.

A reliable field monitoring system is not only used to monitor and protect from illegal land use changes but can also help monitor the

TABLE 2. SUMMARY OF THE PRACTICAL APPLICATION OF PA IN OIL PALM PLANTATION

Parameters of PA applications	Practical application in oil palm plantation
Reliable field monitoring system	Innovative development in oil palm seedling nursery (Lahuri et al., 2021); Drone technology in oil palm plantations (Khuzaimah et al., 2022); Monitoring oil palm plantation blocks (Yuniasih et al., 2019); GIS data collection for oil palm with smartphone-based (Abdullah & Muhadi, 2015); Prediction of palm oil yields using machine learning (Khan et al., 2022); Modelling oil palm phenology based on remote sensing (Hernawati et al., 2022); Oil palm detection using satellite imagery (Nurmasari & Wijayanto, 2021); Multisensor approach to monitoring oil palm plantation (Pohl et al., 2015).
Database management system	The framework of oil palm PA (Fairhurst et al., 2003); Agronomic management information system (Tropical Crop Consultants [TCCL], 2010); Oil palm gene database (Sanusi et al., 2018); Information system for oil palm breeding (Fauzi et al., 2020).
Transparency and traceability system	Standard methods to trace agriculture products based on data centres (Cheng et al., 2013); Tracing and tracking agricultural batch products (Ruiz-Garcia et al., 2010); GPS-based trace and track and sustainable global supply chains (Kandel et al., 2011); RFID application strategy in agri-food supply chains (Zhang & Li, 2012); Enabling technology for food supply chain transparency (Astill et al., 2019); Chemical and biological sensors for food monitoring and intelligent packaging (Mustafa & Andreescu, 2018); Food traceability and transparency using blockchain (Yiannas, 2018).
Site-specific agriculture	Variable rate sprayer for oil palm plantation (Ishak et al., 2011); Diagnostic tools for optimising fertiliser (Dubos et al., 2019); Oil palm water balance tool (Safitri et al., 2017); Variable rate application in palm oil (Ishola et al., 2012).
Decision support system	The decision support system in agriculture (Zhai et al., 2020); Data life cycle management supported by information and communication technology for decision-making (Demestichas & Daskalakis, 2020); Expert system in oil palm PA (Tan et al., 2022).

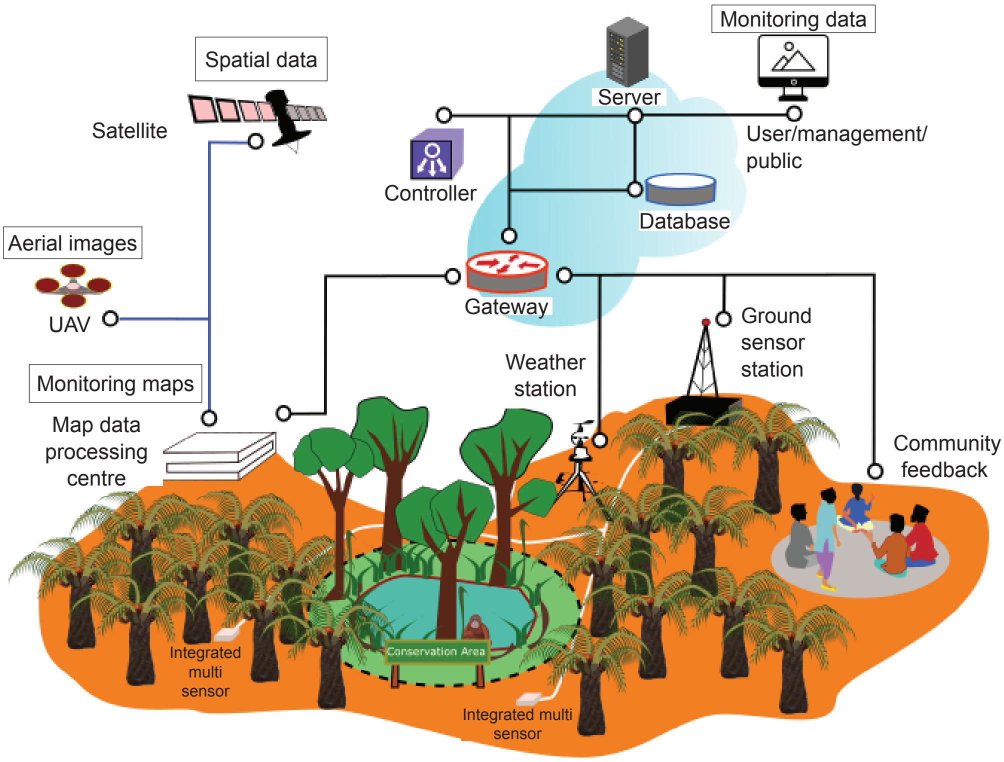

Figure 2. An alternative concept of PA for monitoring oil palm plantations.

comprehensive condition of the oil palm plantation more effectively. For example, the use of UAVs or drones for monitoring, crop yield assessment, spraying, health assessment, weed mapping, irrigation management and disease detection since UAVs can produce a high-resolution aerial photograph with more economical operational cost, rapid and more accurate than the manual method (Norasma et al., 2019). These technologies can also be used inexpensively for surveillance in marking planted areas' boundaries, thereby avoiding land legality problems, especially for smallholders. The capability of drones or UAVs to do 3D mapping makes it possible to do geological surveying, topographic mapping, volumetric calculation and generate site images in 3D format. The UAV application is also decisive for observation, tree counting and layout preparation for replanting (Khuzaimah et al., 2022).

GIS can handle spatial data containing geo-references and time-references. GIS has lower operating costs than UAV since the map data can be downloaded from satellite operators; some are paid, but some are free. The Sentinel-2 and Landsat-8 optical satellite imagery can be used in Indonesia (Nurmasari & Wijayanto, 2021). Some developers have just developed a smartphone-based mobile app to monitor *Ganoderma* disease based on GIS data (Abdullah & Muhadi, 2015). GIS and GPS can be used for data modelling and predicting or building an automated system by incorporating multiple sensors. The data from weather stations and soil data from sensors with time references and geo-references can be used for predicting oil palm yields. The data are compiled and modelled using machine learning to predict the future trend (Khan et al., 2022). The most interesting is that the data interpretation result has high accuracy. Multisensory data from optical and radar remote sensing satellites can improve tree classification accuracy by up to 96%. It means that the data provide a more complete perception of the object and more complete information (Pohl et al., 2015). The most recent example was reported by Lahuri et al. (2021), who described the management of multiple tools and sensors to develop an intelligent farming system for oil palm seedlings in a wide area. The micro-sprinkler powered by the solar system was controlled using the Internet of Things (IoT) application and operated automatically based on soil humidity, temperature and pH. There is a GIS system that ensures the location of the tree. Every tree gets the appropriate water, fertiliser, and herbicide in accordance with its needs.

Database Management System

Many oil palm industry stakeholders in Indonesia believe that digital transformation can escalate production performance and reduce costs.

The digital transformation will streamline field data collection and statistical tasks, enabling real-time execution (Haryanti et al., 2021). The database has an essential role in making a decision. The user records all required information in regular structured information, which can be used as a basis for decision-making (Çelikyürek et al., 2019). Growing awareness of managing big data from the plantation for continuous improvement is happening in Indonesia. Several domestic companies have developed technology to collect and manage data in oil palm plantations by using information system technology. A reliable database management system (DBMS) is needed because the palm oil industry has an extended production chain (Yuwono, 2020). Reliable DBMS should have many methods of keeping records, keeping data for a long time, reusing data when needed, accessing data quickly, filtering records according to specific features and sharing data among users efficiently (Costa et al., 2022).

A DBMS is a tool to store and analyse intricate datasets. The field monitoring system generates numerous datasets encompassing seedlings, planting, harvesting and replanting stages. DBMS in agriculture can store information such as soil maps, farm maps, landscape maps, annual field maps, crop records, environmental conditions, weather conditions, pest records, fertiliser applications, chemical records and flood maps (Sarmah et al., 2018). The datasets collected in oil palm plantations should have geo-references and time references. The data usually consist of soil and land mapping, FFB production, fertilisation dose, environmental sampling, pests and diseases, palm census and climate (Fairhurst et al., 2003). Accurate and reliable DBMS could record and manage datasets for many years. The output of DBMS should be reliable and ready to be used by management for evaluating, planning and forecasting. The meaning of reliability includes the ability to recover in the event of system failure, having suitable security mechanisms and can be integrated with the existing systems (Gunjal & Koganurmath, 2003). An example of DBMS implementation in oil palm plantations is the agronomic management information system (AIMS). AIMS is integrated software that stores and processes data in oil palm plantations using SQL and GIS-compatible software. This system has been used widely by oil palm companies and has been proven to assist the decision-making process by top management (TCCL, 2010).

Transparency and Traceability System

Trade barriers have become an external challenge that haunts Indonesian palm oil exports. The most apparent issue is transparency and traceability since the importers, mainly from the EU, demand apparent food safety and sustainability assurance from the CPO exporters (Gunawan et al., 2021). Moreover, transparency and traceability have been listed in the RSPO as tools to ensure reliability and sustainability by knowing exactly how palm oil flows through the supply chain, including which mills and plantations process the palm fruit and kernels (Voora & Andrade, 2016). The new ISPO also implies transparency and traceability in sustainability implementation practices, though not as clear as the RSPO. Although there is a risk that this change will make it even more difficult for smallholders to implement the new ISPO, this policy is still a mandatory regulation (Purwanto, 2020). Following the fact that the commitment to transparency and traceability principle in Indonesia is still low since the percentage of plantations that have successfully implemented ISPO is still under 50% (Hasnah et al., 2021).

Transparency is how all parties can monitor and perceive how the industry operates by applying the principle of sustainability. Transparency and traceability are required in modern agriculture to ensure food safety and improve supply chain transparency (Cheng et al., 2013). Traceability is the ability to trace an entity's history, application, or location through recorded identifications. It means the customer can trace the origin of the palm oil they consume. The agricultural process data service with transparency and traceability capability usually consists of data acquisition, data transfer, data storing and analysis, data transfer interface and data user utilisation (Ruiz-Garcia et al., 2010).

Data acquisition with manual tracking still exists in the current food supply chain. A prominent example is oil palm surveying to monitor the soil and palm trees' health, ecosystem balance, existing pests and water source conditions, primarily conducted using manual field inspection methods. However, automated data acquisition will be preferred in the future using the newest technologies, including various sensors, vocalisation analysis systems and imaging technologies. The most recent example is the utilisation of GPS and RFID in the supply chain, which have been widely implemented to retrieve the time and location of the product. This technology gives assurance for real-time visibility, from the raw material to the end product, which may reduce food contamination and spoilage (Kandel et al., 2011). Besides that, IoT's utilisation for data transfer to data storage and big data analytics that can provide deeper comprehensive decision options with minimal errors has already been implemented in agricultural supply chain management (Astill et al., 2019). These examples show that the technology that supports the transparency and traceability requirements has been proven and is ready to be implemented in oil palm plantations.

Site-specific Agriculture

The use of production inputs such as fertiliser doses, pesticide doses, organic matter and the number of workers can affect the yield of FFB. There is often inefficiency in using these inputs, especially among smallholder farmers in Indonesia (Maulida et al., 2022). Site-specific management in PA aims to optimise water, fertiliser, herbicide and other inputs into the field. Furthermore, excessive inputs in agriculture can pollute the environment. Three mandatory things to do in site-specific management are knowing the position, gathering live information at the location and conducting the variable rate application. GPS is a standard system for knowing the location. Gathering information like yield monitoring, soil electrical conductivity (EC) condition, remote imagery, soil compaction sensing, or soil pH condition is conducted using sensors at sequential times and with geo-references. Variable-rate controllers can be applied for any required inputs. The inputs are spread with varying doses as needed at each point in a specific location that has been gathered previously (Franzen, 2018). There are some methods for collecting and interpreting data in the PA implementation. Dubos et al. (2019) used long-term fertilisation data to diagnose the sustainability of nitrogen (N) and potassium (K) in the soil since both are important for oil palm trees. This data was linked to past yield data and mature period data to detect the depletion of soil nutrient reserves. This method can predict soil nutrient conditions before measuring the actual soil nutrient condition in the field to avoid the risk of excessive fertilisation without hindering FFB production.

Another example of site-specific agriculture is using a water balance model to predict water content distribution in the root zone. The water balance tool is developed by inputting the data on climate, soil properties, crop stage, root density and root zone layer. Then, this data is modelled to conceive water behaviour in the root zone. This method can be a tool for knowing the actual water needs in the oil palm root zone (Safitri et al., 2017). An example of variable rate application implementation in oil palm plantations was shown by Ishak et al. (2011) , who developed a variable rate sprayer for herbicide application based on colour detection from camera vision. The camera vision is used to distinguish between weeds and palm trees and calculate the percentage of weeds in a particular location. Thus, the computer controller decided the amount of herbicide application. This application was expected to make a site-specific application for reducing the use of herbicides. This application can also be implemented in other liquid inputs such as fertiliser or insecticides.

Decision Support System

PA implementation needs massive and integrated infrastructure to take data from the field, send and store it in the database, be accessed and tracked by concerned parties and apply site-specific application inputs for optimisation. When all these different parameters of PA are already running, this is then the appropriate time to implement a decision support system. An agricultural decision support system (DSS) is a human-computer system that utilises data from various sources to provide farmers with many optional recommendations for supporting their decision-making under different circumstances. Although the system gives recommendations, the farmer still chooses the decision. The agricultural DSS has become more critical since changes in the climate, soil nutrient balance, water balance, pest attack and other conditions have affected the sustainability and productivity of oil palm plantations (Ren et al., 2022).

The general framework of agricultural DSS can involve many aspects of the dataset and can utilise different types of machine learning to enhance capabilities, as shown in *Figure 3*. The DSS can cover field data models, such as crop and irrigation models, and can be influenced by economic and human intervention factors (Zhai et al., 2020). The recommendation options can be generated based on the dataset stored in a database that fits the data lifecycle model. The data lifecycle model may consist of data collection and the IoT, data analysis and artificial intelligence, and data storage and distribution. The quality of the data life cycle model will influence the quality of the DSS output (Demestichas & Daskalakis, 2020). Agricultural DSS can also give the farmer recommendation options based on big data on planting seeds, managing transportation in the field, managing irrigation, applying inputs (fertiliser, herbicides, insecticides), or predicting labour needs (Tan et al., 2022).

The Challenges in Indonesia

PA practices have been implemented in Indonesia, especially in plantations managed by big corporations. However, smallholders still have limitations in implementing PA in their plantations (Ginting & Wiratmoko, 2021). The number of plantations managed by smallholders and plasma is large. Based on data from BPS Indonesia, (2021), almost 42.0% of palm oil plantations in Indonesia are smallholder holdings with limited ability to implement ISPO. Though the new ISPO is mandatory for every plantation in Indonesia, only 33.0% of the total oil palm area obtains ISPO certificates, and those are mostly from plantations managed by big corporations. The oil palm

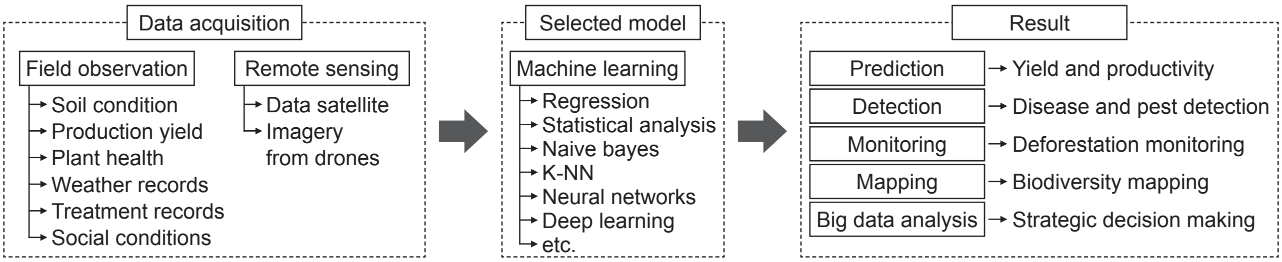

Figure 3. The instance of data flow for palm oil decision support system.

plantations, primarily owned by smallholders and plasma farmers, still need assistance implementing ISPO (Hasnah et al., 2021). The smallholder's readiness to conduct environmental management, monitoring, and continuous improvement as part of ISPO implementation is still low. Only 60.9% of ISPO indicators had been applied by smallholders using gap analysis. The lowest percentage of implementation is environmental management and monitoring principles, with only 43.0% that can be fulfilled (Soebirin et al., 2021).

It is undeniable that PA implementation requires expensive investment costs. Some tools of PA and cost estimation can be seen in *Table 3*. The utilisation of UAV technologies has various technical issues that must be considered: The need for expert pilots and data processing teams, the high-speed ultra-low scenario, data downloading tasks in a real-time application, size and payload to prevent obstructions and software for automatic analysis. In addition, it requires an expensive initial investment (Khuzaimah et al., 2022). Similar difficulties will be encountered when building field monitoring systems integrated with the database system to ensure transparency and traceability. A reliable transparency and traceability system needs a suitable arrangement of the successive links between batches and logistic units throughout the supply chain. Data standardisation among stakeholders along the supply chain is required and the consequence is that they should have infrastructure and process standards that make it integrated (Ruiz-Garcia et al., 2010).

The economic sustainability of the oil palm industry can be affected due to the activation of a transparency and traceability system associated with new costs and risks. Oil palm plantations have a long supply chain involving various sectors hence making it difficult to standardise the requirements among the stakeholders except in large companies with integrated infrastructure from upstream to downstream. Moreover, there are some barriers to ensuring effortless flow of data streams and smoothly from the downstream to upstream and, ultimately, to the customer due to the lack of IoT connectivity, the complexity of the supply chain, and economic sustainability (Astill et al., 2019). It relates to Indonesia's conditions since more than 40% of oil palm plantation areas in Indonesia are blank spots or have no internet connection, particularly in the hinterland (Redaksi Sawit Indonesia, 2022).

Human resources readiness is another challenge because plantation workers' rejection, social and cultural rejection, and low advanced technology adaptability are still common in oil palm plantations. The education level of plantation workers is varied, forcing plantation managers to expend more effort to implement PA. Even more, there is an assumption that PA can reduce employment, causing workers' rejection (Ginting & Wiratmoko, 2021). There is a need for more research to produce new technologies that fit with the socio-cultural character and nature of oil palm smallholders in Indonesia. High expectancy comes from the young farmers being more adaptable to new technology since they respond better to PA implementation. However, the number of young generations in Indonesia interested in agriculture is becoming less and less (Sondakh et al., 2021).

Palm oil data often differ due to methodological differences and data processing criteria, and the Ministry of Agriculture has been synchronising data from the palm oil stakeholders (Republika, 2019). Asynchronous data among stakeholders can also be an obstacle in decision-making and the implementation of PA. Considering the high expectations of PA applications to support sustainability and productivity, the Government should be bridging and setting up the infrastructure and standards, especially for the smallholders, so that PA can be applied nationally. If the infrastructure for implementing PA cannot be built simultaneously, it should start by developing a pilot project in a small area first. It would be better if that pilot project is integrated with the development strategy of the Indonesia palm oil industrial cluster (POIC).

The idea of POIC is to cluster the palm oil industry to become more competitive and organised. Clustering is applied to the palm oil industry in Indonesia to improve competitiveness and

TABLE 3. SOME TOOLS OF PA IMPLEMENTATION AND COST ESTIMATION

Tools	Function	Cost
Drone	It can be used for monitoring vegetation levels, monitoring vegetation stage, oil palm tree detection, estimating chlorophyll density, crop health monitoring, drone spraying, crop growth monitoring and harvest prediction (Khuzaimah et al., 2022).	Based on the latest research, the average price of drones worldwide in 2023 will be around USD530 (Laricchia, 2023). However, the prices can vary depending on the type of drone. A high-end drone, like the Dji Matrice 350 RTK, can cost more than USD17,000.
Satellite data	Retrieve data from satellites like Landsat, Modis, UK-DMC 2 Imagery Data, Worldview -2 multispectral data, LiDar, Palsar-1, Palsar-2, etc. The satellite data can be used for remote sensing to observe, analyse and assess the landscape conditions of oil palm plantations (Tan et al., 2022).	The cost of satellite data can vary widely depending on several factors, such as resolution, area of interest, sensor type, date of acquisition, licensing and usage. Landsat data with multispectral imagery can be obtained for free with limited resolution. However, more spectral and higher-resolution imagery can be obtained at a cost, like Worldview-3 with 8-band multispectral imagery for USD48 per km^2 (Land Info, 2024).
GPS (Global Positioning System) and GNSS (Global Navigation Satellite System)	GPS or GNSS are key tools to develop specific location data for PA. Data received from GPS or GNSS becomes mandatory for implementing GIS or carrying out site-specific treatment.	The price of GPS can vary depending on its accuracy. GPS with an accuracy of 50 m can range from around USD100–USD500. But for devices that have an accuracy of one to two metres, they can reach USD25,000 (FieldBee, 2022)
Sensors	Sensors are usually coupled with an IoT system for real-time field monitoring. The types of sensors used can vary. They can be soil sensors, environmental sensors, or multispectral camera sensors that take pictures of oil palms to monitor environmental conditions and oil palm plantation crops (Tan et al., 2022).	The cost of sensor technology may vary, but the trend is declining. The accelerometer sensor for plant monitoring can cost USD87–USD430. Infrared sensors can cost USD24–USD188 (Lahuri et al., 2021). Soil sensors may vary from 10 USD for basic models and can be over thousands of dollars for high-end sensors with data logging systems (NiuBol, 2023).
RFID (Radio Frequency Identification)	RFID in oil palm plantations is very useful to improve traceability, efficiency and data management. It can be used for plant tracking and inventory management, harvesting and fruit tracking, supply chain management, worker identification and safety.	The cost of building a system with RFID may vary depending on the scale, type of RFID and method of integration in the information system. The cost of passive RFID ranges from USD0.1–USD1.5 per tag, while the cost of active RFID ranges from over USD10 per tag. However, there are other costs besides the price of tags, such as the reader system, which for passive RFID can reach USD3,000, installation costs, software, and licences (Halstead, 2023).
Decision support system	A system that collates various data from sensors, remote sensing, field observations, and other data into meaningful information. DSS is able to optimise solutions, identify situations, analyse alternative strategies and find data correlations (Rinaldi & He, 2014)	The main costs incurred in applying a decision support system are infrastructure and labour costs. The amount of cost depends on the framework used, the scale of the project, the level of complexity, the cost of data acquisition and expert wages in a particular country.

increase the value of palm oil production (Yahya & Gunawan, 2020). Malaysia and Indonesia have POIC, which is now continually developed. POIC in Indonesia has a larger plantation area than in Malaysia, indicating a larger potential production capacity. However, the infrastructure and logistic network of POIC in Indonesia is more underdeveloped than in Malaysia (Raharja et al., 2021). As a priority development, the POIC plan in Indonesia can align with the functions and objectives of developing PA by developing supporting infrastructure, creating global connectivity, increasing transparency, improving infrastructure and increasing product innovation (Raharja et al., 2021). Implementing PA in the new POIC will be more easily integrated with all lines of business processes than building connectivity on long-established plantations.

CONCLUSION

PA implementation has the potential to be a breakthrough for maintaining the sustainability and productivity of oil palm plantations in Indonesia. The PA performance can encourage the readiness of the oil palm industry to implement ISPO and RSPO because of its ability to carry out monitoring and surveillance in the field, connect with many users in real-time and retrieve and process data for evaluation and decision-making. Five parameters of PA implementation are proposed in the oil palm plantations: A reliable field monitoring system, a database management system, transparency and traceability, site-specific agriculture, and a decision support system. Smallholders and plasma plantations have the biggest challenge in leveraging precision farming practices. The barriers to implementing PA in Indonesia include more investment costs, an inadequate number of experts, lack of infrastructure, socio-cultural rejection, refusal by farmers and workers and the need for business process synchronisation among the stakeholders for running an integrated PA. If it cannot be implemented simultaneously, the best suggestion is to start with a small pilot project that can be integrated into the POIC strategy, which will develop new plantations with an industrial cluster system.

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