Review Article

Engineering-Science Driven Review of Field Maintenance Machinery in Indonesian Oil Palm Plantations: Performance Metrics, Governing Processes, and Research Needs

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https://doi.org/10.22067/jam.2026.97821.1472

Abstract

Oil palm supports Indonesia's rural economy, yet field maintenance operations remain labour-intensive and measurement sparse. This engineering science driven review synthesises 20 studies published during 2015–2025 on weed control, fertiliser application, pest and disease management, pruning/canopy work, and supporting soil/residue operations in Indonesian oil palm. To handle heterogeneous reporting, performance indicators were classified as directly reported metrics, derived metrics, proxy indicators, or not reported; no missing values were imputed for CV, deposition, drift, or droplet spectrum descriptors. Across the available evidence, electric/motorised sprayers, CDA systems, and UAV spraying generally reduced time and/or cost relative to manual knapsack practice, while tractor towed spreaders, pneumatic applicators, and subsurface placement concepts improved dosing and targeting in fertiliser operations. However, only a minority of studies reported standardised engineering metrics such as CV, VMD, on target deposition, drift, or operator exposure. The review provides a structured engineering comparison rather than a formal meta-analysis and identifies priority research needs: standard test protocols, comparable benchmark reporting, and modular multifunction platforms integrated with sensing, decision support, and service-based deployment models.

Keywords: Field maintenance, Machinery, Modular concepts, Oil palm, Precision agriculture

Introduction

The oil palm industry plays a critical role in the national economy, yet it continues to face major productivity and sustainability challenges (Mulyasari, Djarot, Sasongko, & Putra, 2023; Papilo *et al.*, 2022; Purnomo *et al.*, 2020; Putri *et al.*, 2022; Suhardjo, Akroyd, & Suparman, 2025; Suhardjo & Suparman, 2026). Agricultural mechanization has been shown to improve operational efficiency (Rahim, 2015; Wijayanto, Afira, & Nurkarim, 2022), reduce dependence on manual labour (Septiarini *et al.*, 2021), and support more environmentally sound management practices in oil palm plantations (Herdiansyah *et al.*, 2023). However, in Indonesia, research and development on agricultural machinery have focused mainly on planting (Adriansyah, 2024; Dahliani, Wirandayu, & Dewantara, 2022; Sarzynski, Giam, Carrasco, & Lee, 2020), harvesting (Dahliani *et al.*, 2022; Danylo *et al.*, 2021; Hamsi, Sitorus, & Isma, 2020; Hanif, Han, & Yu, 2022), and post-harvest processing (Aminuddin, Nurrohkayati, & Rohmatulloh, 2024; Hamsi *et al.*, 2020; Rahutomo *et al.*, 2020), while field maintenance technologies have received comparatively limited attention. As a result, a knowledge gap remains in the development and application of machinery specifically designed for oil palm field maintenance. Although maintenance practices have been widely studied, most studies emphasize socioeconomic (Qaim, Sibhatu, Siregar, & Grass, 2020; Ramadhana, Ahmed, & Thongrak, 2021;

Supriatna, Djumarno, Saluy, & Kurniawan, 2024) and environmental dimensions (Khofiyah, Sutopo, & Hisjam, 2020; Kholis, 2021) rather than machinery and engineering oriented innovation.

Oil palm field maintenance presents a distinct engineering problem because machine selection and performance must accommodate heterogeneous terrain and soil conditions while limiting adverse effects, such as soil compaction and unnecessary field disturbance (Ibrahim, Khalid, Radzi, & Bakri, 2024). This matters because maintenance operations such as weed control, fertilisation, and pruning are recurring parts of plantation management that directly affect yield and profitability, yet they remain less systematically mechanised than planting, harvesting, and post-harvest operations in the broader oil palm mechanisation landscape (Woittiez *et al.*, 2024).

Existing literature on oil palm machinery remains fragmented, with much of the synthesis concentrated either in broad pre-harvest bibliometric mapping or in technology-specific reviews, such as drone-based applications in plantation management (Khuzaimah *et al.*, 2022). Unlike those adjacent reviews, the present manuscript focuses specifically on field maintenance machinery and compares technologies through common engineering metrics, governing processes, and measurement gaps. This maintenance-specific lens is important because design lessons are otherwise difficult to transfer across studies when reported indicators differ in units, completeness, and experimental context.

From an engineering standpoint, the key question is not only whether mechanisation improves efficiency, but which design and operating variables control performance under plantation conditions. Spray systems depend on pressure stability, droplet spectrum, travel speed, and target interception; fertiliser applicators depend on metering stability, distribution pattern, and placement accuracy (pruning tools depend on cutting energy, cycle time, and operator fatigue). A review that links these governing processes to reported outcomes is needed to move beyond descriptive claims that machines are merely faster or cheaper.

This review addresses that need by synthesising Indonesian field maintenance machinery studies using a transparent review workflow and a set of minimum engineering metrics. Rather than assuming full comparability across studies, we distinguish directly reported metrics, derived metrics, proxy indicators, and missing variables, and we interpret the evidence through operational capacity, application quality, losses/risk, energy cost, and operator exposure lenses. The objective is to identify what is already known, what remains weakly measured, and which research directions are most likely to produce transferable design rules for Indonesian oil palm conditions.

Fig. 1. Schematic illustration of the scope of this review on developing agricultural machinery and equipment for field maintenance activities in oil palm plantations in Indonesia

Materials and Methods

Review design and scope

This integrative review synthesised evidence on the engineering development, field performance, and adoption constraints of agricultural machinery for oil palm field maintenance operations in Indonesia. The review covered studies published from 2015 to 2025, prioritising Indonesian publications to capture local mechanisation progress and constraints, while using selected international literature for benchmarking emerging technologies (e.g. UAV spraying, automation, and sensor-based systems). The scope comprised five maintenance domains: (i) weed management, (ii) fertiliser application, (iii) pest and disease control, (iv) pruning/canopy management, and (v) supporting soil/residue operations relevant to maintenance. In addition to data extraction, we applied a critical appraisal framework that records (i) the design/control variables tested, (ii) the engineering performance metrics reported (e.g. uniformity/CV, deposition, drift, energy), and (iii) the strength of evidence (experimental design, replication, and field conditions), so conclusions are engineering-science driven.

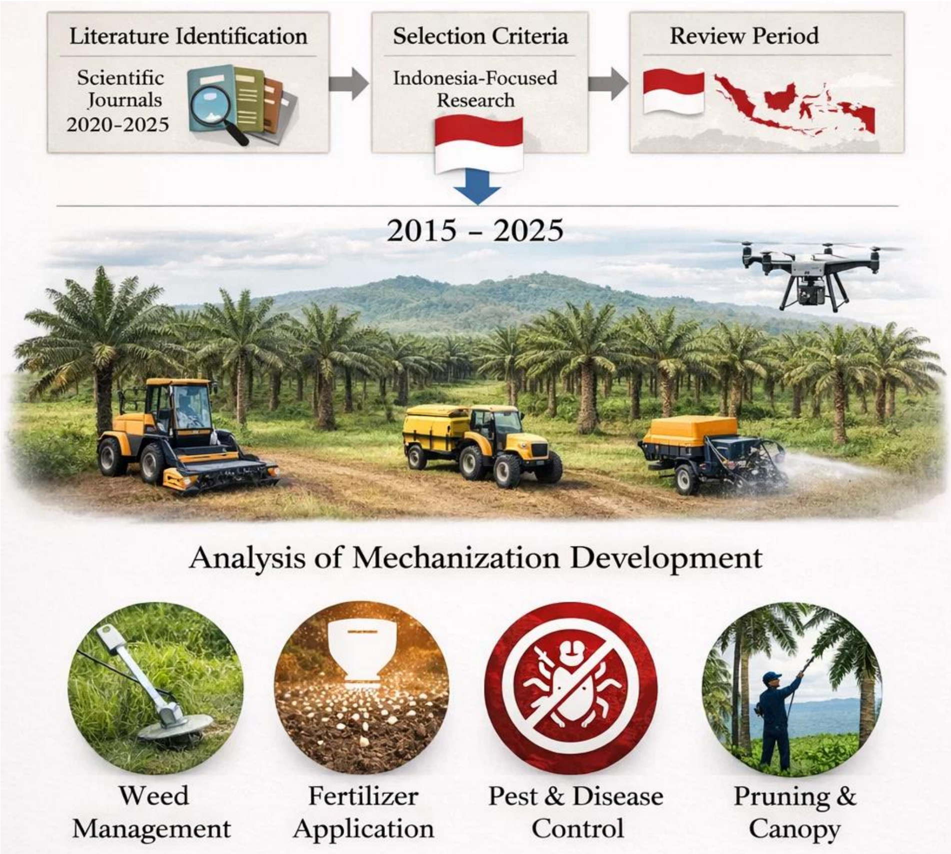


Fig. 2. Design and scope

Information Sources and Search Strategy

A structured literature search was conducted in 2025 across Scopus, ScienceDirect, and Google Scholar using English and Indonesian keywords with Boolean operators. Representative search strings included: ("oil palm" OR "Elaeis guineensis") AND (mechanization OR machinery OR equipment OR sprayer OR "controlled droplet" OR "drone sprayer" OR fertilizer spreader OR pneumatic applicator OR fogger OR pruning OR egrek OR dodos OR "canopy management" OR residue OR mulcher) AND (Indonesia OR Indonesian); and ("kelapa sawit" OR "Elaeis guineensis") AND (mekanisasi OR alsintan OR alat OR mesin OR sprayer OR drone OR pemupukan OR penabur OR pengabut OR pemangkasan OR egrek OR dodos OR pelepah OR pencacah OR mulcher). Citation tracking of key papers was applied to identify additional relevant studies.

Eligibility Criteria and Selection

Studies were included if they (1) were published in 2015–2025, (2) addressed oil palm plantations, (3) evaluated machinery/equipment or mechanized systems relevant to field maintenance, and (4) provided engineering-relevant information (e.g. configuration/design, operational workflow, performance metrics such as field capacity, coverage/uniformity, droplet features, effectiveness/mortality, fuel/energy use, labour, cost indicators, and/or adoption/feasibility). Eligible sources included empirical studies, prototype/engineering reports with clear methods and results, operational evaluations, theses, and peer-reviewed conference proceedings. Studies were excluded when they lacked a mechanization part (e.g. agronomic input comparisons only), were method-free opinion pieces, or were outside field maintenance operations (unless directly supporting maintenance objectives). Records were de-duplicated and screened in two stages (title/abstract followed by full text), with disagreements resolved by author consensus; the overall method and study selection workflow are summarized in Fig. 3.

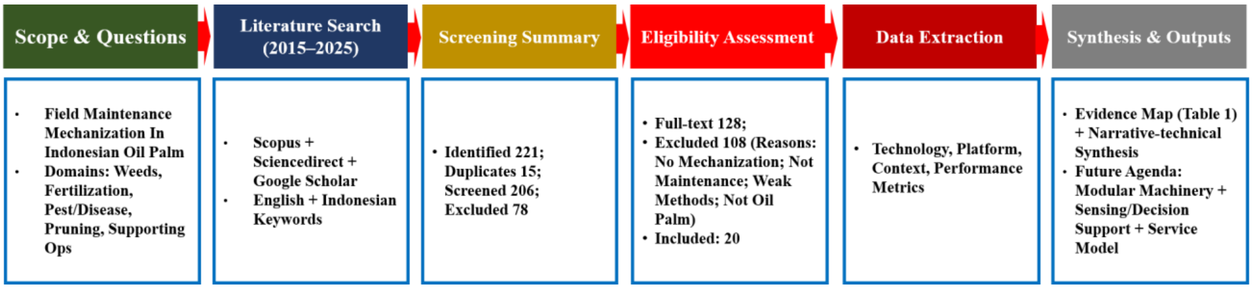


Fig. 3. Methodology framework and study selection summary for the integrative review (2015–2025)

The workflow comprises scope definition, database searching (Scopus, ScienceDirect, Google Scholar), screening, eligibility assessment, data extraction, and synthesis outputs. The screening results were 221 records identified, 15 duplicates removed, 206 screened, 78 excluded, 128 full texts assessed, 108 excluded (reasons: no mechanization part, not field maintenance, insufficient methods, not oil palm), and 20 studies included.

Data Extraction and Synthesis

Data were extracted using a standardised sheet covering: domain/operation type; machinery category and key parts (power source, actuation, delivery mechanism/nozzle type, mobility platform); field context (estate vs smallholder, terrain/topography, palm age/height); reported performance indicators (capacity, effectiveness, distribution quality, energy/fuel use, labour, cost, safety/ergonomics); and adoption enablers/constraints (service and spare-part availability, operator skills, capital cost, maintainability, and suitability for heterogeneous smallholder settings). Each indicator was then classified as directly reported, derived from minimum supporting variables, proxy-based, or not reported (NR). Evidence was synthesised through (i) evidence mapping by domain (Table 1) and (ii) narrative-technical comparison of solution types to identify consistent bottlenecks, performance trade-offs, and research gaps. The synthesis informed an integrative agenda emphasising modular multi-function machinery and integrating sensing/decision support with scalable service models for Indonesian conditions.

Quantitative Performance Framework and Metric Standardization

To enable consistent cross-technology and cross-study comparison, mechanized oil palm maintenance is assessed using measurable and formalizable performance metrics. For the main maintenance domains (herbicide/pesticide spraying, fertilizer application, and pruning/field operations), the minimum metric set is grouped into: (i) operational capacity/productivity, (ii) application quality (uniformity, coverage, and on-target deposition), (iii) losses and risk indicators (drift/loss proxies), and (iv) energy and cost per hectare. When studies did not report a complete metric set, we kept direct measurements, calculated derived values only when the minimum required variables were available, used proxy indicators for mechanistic interpretation, and left the remaining metrics as NR (not reported) rather than imputing them.

Effective Field Capacity

Effective field capacity (EFC) is defined as treated area per total operating time, including turning, refilling, and delays. A practical form based on travel speed and effective working width is also used, with field efficiency capturing non-productive time.

Effective field capacity (EFC)

$$EFC = \frac{A}{t_{tot}} \quad (1)$$

where A is the treated area (ha) and t_{tot} is the total operating time, including refilling, manoeuvring, and idle periods (h).

where t_{tot} represents the treated area (ha) and t_{tot} denotes the total operating time, including refilling, manoeuvring, and idle periods (h).

A practical form based on operating speed and effective working width

$$EFC = \kappa . v . W . \eta_f \quad (2)$$

where v is forward speed, W is effective working width (m), η_f is field efficiency, and k is the unit-conversion factor (e.g. from m s^{-1} and m to ha h^{-1}).

where v denotes the forward speed, W is the effective working width (m), η_f represents field efficiency, and κ is the unit conversion factor (e.g. from m s^{-1} and m to ha h^{-1}).

Equations (1–2) enable the normalisation of productivity metrics across different studies, allowing consistent comparisons among technologies (manual, motorised, CDA, and UAV).

Application rate and distribution uniformity (spray or fertiliser)

For spraying or liquid application, the application rate relates the total flow rate to travel speed and swath width. Distribution quality across sampling points (e.g. tray/pan tests for fertilizer or deposit/coverage sampling for spraying) is expressed using the coefficient of variation (CV).

$$R_{app} = \frac{Q}{v \cdot W} \quad (3)$$

where R_{app} denotes the application rate (volume per unit area) and Q represents the flow rate (volume per unit time).

$$CV(\%) = 100 \cdot \frac{\sigma}{x} \quad (4)$$

where x denotes the mean deposit (or captured mass) at the sampling points and σ represents the standard deviation.

Coverage (surface coverage on-target)

To interpret how droplet spectrum and operating settings affect spray outcomes, a simple coverage model is included as a mechanistic link between droplet number density and areal coverage. On-target deposition efficiency is defined as the fraction of applied active ingredients that deposit on the intended target; residual fractions are treated as losses (e.g. drift and runoff).

$$C = 1 - exp(-\lambda), \quad (5)$$

with

$$\lambda = N_d \cdot A_d$$

where C is the fractional coverage (0–1), N_d is the number of droplets affecting the target per unit area (droplets m^{-2}, and A_d is the effective footprint area per droplet (m^{-2}). A practical approximation is $A_d = \pi \left(\frac{de}{2}\right) 2$, where d_e is an equivalent droplet diameter (m). Equation (5) captures the expected saturation behaviour: coverage increases with droplet density and footprint but approaches an upper limit as overlaps become frequent.

On-target deposition efficiency (target capture efficiency)

On-target deposition efficiency is defined as the fraction of applied active ingredient (or tracer) that deposits on the intended target:

$$\eta_{dep} = \frac{M_t}{M_{app}} \quad (6)$$

where M_t is the mass of active ingredients (or tracer) measured on the target (e.g. leaf samples, collectors, water-sensitive cards, or trays) and M_{app} is the mass applied (e.g. concentration × spray volume delivered).

Loss partitioning (drift/runoff/other losses)

Total loss can be expressed as the complement of deposition efficiency and, when data permit, partitioned into drift and runoff/ground losses:

$$L_{tot} = 1 - \eta_{dep}; L_{tot} = L_{drift} + L_{runoff} + L_{other} \quad (7)$$

where L_{drift} is the fraction transported outside the target zone by wind, L_{runoff} is the fraction lost via runoff/drip, and L_{other} includes other loss pathways (e.g. mixing/refill losses, bounce, or very fine-droplet evaporation when relevant). Equations (6)–(7) provide a mass-balance language to support consistent cross-technology discussion of "on-target deposition" and "drift losses".

Droplet size spectrum descriptors (VMD and

span)

Because the droplet spectrum strongly governs drift potential, canopy penetration, and deposition outcomes, the volume median diameter (VMD) is used to represent the central tendency of droplet size:

$$D_{v0.5} = VMD \quad (8)$$

A convenient descriptor of spectrum breadth is the relative span:

$$RS = \frac{D_{v0.9} - D_{v0.1}}{D_{v0.5}} \quad (9)$$

where $D_{v0.1}$, $D_{v0.5}$, and $D_{v0.9}$ are droplet diameters at 10%, 50%, and 90% cumulative sprayed volume. In synthesis, narrower spectra (lower RS and appropriately selected VMD can improve uniformity and reduce off-target losses, while very fine sprays (low VMD) increase drift risk.

Drift potential index (fine-droplet fraction proxy)

When studies do not quantify drift directly, a practical proxy is the fine-droplet volume fraction below a threshold diameter $d*$ (commonly 100–150 µm depending on reporting conventions):

$$\mathrm{DPI} = \frac{V_{\leq \mathrm{d}*}}{V_{\mathrm{tot}}} \quad (10)$$

where $V_{\leq \mathrm{d}*}$ is the total droplet volume with a diameter less than $d*$, and V_{tot} is the total sprayed volume. Larger DPI indicates greater drift potential, which is useful for comparing knapsack/motorized sprayers, CDA systems, and UAV applications under different boom/flight heights and wind conditions.

Outcome efficacy

Where biological outcomes are reported (e.g. weed mortality or reduction in pest incidence), efficacy can be expressed as a relative reduction from baseline or control:

$$E(\%) = 100 \cdot \left(1 - \frac{Y_t}{Y_0}\right) \quad (11)$$

Energy and cost per hectare

Energy and cost are expressed on a per-hectare basis to support comparison across mechanization options and operational scales. Energy per hectare is estimated from fuel consumption and the lower heating value (LHV). Operating cost per hectare is calculated from hourly costs divided by EFC.

Energy per hectare based on fuel consumption:

$$E_{ha} = \frac{(\dot{m}_f \cdot LHV)}{EFC} \quad (12)$$

where $\dot{m}_f$ is the fuel consumption rate (mass per unit time) and LHV is the lower heating value of the fuel.

Operating cost per hectare:

$$C_{ha} = \frac{C_h}{EFC}, \quad C_h = C_{fixed} + C_{var} \quad (13)$$

where C_h denotes the hourly operating cost, consisting of fixed parts (depreciation and capital interest) and variable parts (fuel, maintenance, and labour).

Given that many Indonesian studies report costs on a per-hectare basis or emphasise cost savings, Equations (12–13) help connect adoption claims to measurable productivity and energy demand rather than relying only on qualitative statements such as “faster” or “cheaper”.

Handling heterogeneous metric reporting

A major methodological challenge in this review is that only a minority of studies report a complete and standardised engineering metric set. Directly reported metrics were extracted as published, derived metrics were calculated only when the minimum supporting variables were available, and proxy indicators were kept only for mechanistic interpretation when standardised metrics were unavailable. Metrics such as CV, on-target deposition efficiency, drift fraction, VMD, and operator exposure were marked as not reported (NR) when the underlying measurements were absent. No missing values were imputed. Consequently, the synthesis is presented as a structured engineering comparison rather than a formal meta-analysis with fully harmonised effect sizes.

Operator exposure proxies (inhalation and dermal)

Where exposure measurements are available, operator inhalation exposure can be summarised by time-integrated airborne concentration in the breathing zone:

$$E_{\mathrm{inh}} = C_{\mathrm{air}}\ t_{\mathrm{exp}} \quad (14)$$

where C_{air} is airborne concentration (mg m^{-3} and t_{exp} is exposure duration (h). Dermal exposure can be represented using patch or coverall deposition measurements:

$$E_{inh} = \sum_{i=1}^{n} \frac{M_{patch,i}}{A_{patch,i}} \quad (15)$$

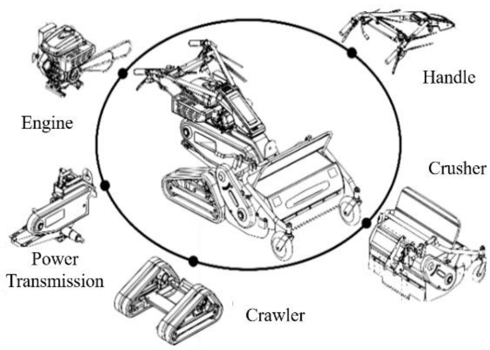
where $M_{\mathrm{patch,i}}$ is the mass collected on patch *i* and $A_{\mathrm{patch,i}}$ is the patch area (m^2). These proxies enable a quantitative discussion of how mechanisation options (e.g. UAV application versus operator carried sprayers) may reduce exposure by separating the operator from the spray cloud.

Recent Advances in Agricultural Machinery for Field Maintenance in Indonesia

Weed Management Machinery

To evaluate spray system advances, we synthesise how controllable variables, such as nozzle or CDA disc type, pressure and flow stability, droplet spectrum, forward speed, boom/flight height, and canopy shielding, translate into application-quality metrics such as coverage uniformity, on-target deposition, and drift loss. In Indonesia, weed control in oil palm plantations is still predominantly carried out using manual and semi-mechanised methods, such as machetes, hoes, or brush cutters. Although several researchers have begun testing higher-capacity sprayers and small tractors equipped with rotary weeders, adoption remains limited by cost, equipment access, and the need to match machine performance to plantation topography, as illustrated in Fig. 4(a). Consequently, much of the domestic literature still focuses more on herbicide choice and application strategy than on the engineering optimisation of dedicated weed management machinery.

(a)



(b)

Fig. 4. (a) Example of a weed-control service device/weed sprayer (Irawan, Azhar, & Sahal, 2022), and (b) Five major elements of the Bull Mower machine (Baharudin *et al.*, 2024)

By comparison, in Malaysia and several developed countries, weed management research has increasingly shifted toward sensor-based autonomous robots (Baharudin *et al.*, 2024), as illustrated in Fig 4(b), and AI enabled drones (Hashim *et al.*, 2020; Khuzaimah *et al.*, 2022; Rodi & Daliman, 2024). These technologies enable more precise and efficient weed control by reducing reliance on manual labour. However, their implementation in Indonesia remains challenging due to high investment costs, limited availability of skilled operators, and the more heterogeneous conditions of smallholder oil palm plantations compared with large, professionally managed estates.

Operationally, weed control mechanisation in Indonesian oil palm plantations is still dominated by herbicide applications using manual knapsack sprayers. As a result, spray quality is highly sensitive to operator stamina, pump pressure fluctuation, and walking-speed variability, all of which can produce uneven droplet distribution and inconsistent dose delivery. To address these limitations, several domestic studies have evaluated electric- or engine-powered sprayers to stabilise discharge pressure and reduce operator pumping variability (Yuliyanto, Kesuma, & Sinuraya, 2017; Silalahi, Zuliyanti, & Siregar, 2023). Electric knapsack sprayers were reported to achieve a use-effectiveness score of 80.27%, with adoption shaped by field conditions, operator skills, extension support, and operating costs. Comparative tests of manual versus motorised knapsack sprayers also showed higher weed mortality (90% vs 99%) and lower cost for the motorised option (IDR 34,610 vs 27,241 ha^{-1}), consistent with improved discharge stability and a more repeatable application pace.

More precision-oriented innovation in Indonesia is emerging through Controlled Droplet Application (CDA) systems that use spinning-disc atomisation and battery/dynamo power to produce a more stable droplet spectrum than conventional manual knapsacks (Suryanto, Vernando, & Soesatrijo, 2022). In those trials, CDA achieved 99% weed mortality versus 90% for the knapsack sprayer, while coverage per tank increased from 188.4 to 1,381.6 m^2 and operating costs declined from IDR 89,436 to 53,508 ha^{-1}. Because the study did not report CV, VMD, or tracer-based deposition, the most defensible interpretation is mechanistic: the CDA architecture likely reduced discharge pulsation and improved droplet number consistency, which would be expected to improve surface coverage and on-target deposition uniformity. At a larger operational scale, drone spraying has shown a different pathway to performance improvement. In replanting fields, drone application reduced spraying time by 82% and cost by 51.6% relative to knapsack spraying, with no significant difference in time to weed mortality (Mahhendra, Mawandha, & Yuniasih, 2025). Taken together, the Indonesian-based evidence suggests two distinct engineering routes: ground-based systems that improve application quality through discharge control and droplet formation, and aerial systems that improve effective field capacity by decoupling coverage rates from operator walking speed.

International literature further indicates that weed management research is advancing toward sensor and computer vision based autonomous robots, including mechanical and laser-based platforms aimed at reducing herbicide dependence and improving control precision. On the detection and decision support side, UAVs combined with deep learning for weed identification (using RGB and/or multispectral imagery) have become an important enabling foundation for precision weeding, supporting hotspot mapping as well as precision or variable-rate spraying (Hanif *et al.*, 2022; Lytridis & Pachidis, 2024; J. Zhang *et al.*, 2024; Zhang, Miao, Li, He, & Sun, 2022). Accordingly, the main research gap for Indonesia is the need for an integrative pipeline that links drone/sensor-based weed mapping, prescription maps for target areas and doses, and application machinery (CDA, boom, or drone platforms) capable of executing reliable variable-rate operations under the heterogeneous conditions typical of smallholder oil palm systems.

Fertiliser Application Machinery

For fertiliser spreading, results are interpreted through granular-distribution engineering: metering mechanism (aperture/auger/valve), discharge stability under speed and slope variability, spreading pattern, and uniformity metrics such as coefficient of variation (CV%). In practice, however, very few Indonesian studies report CVs or full distribution maps; most provide throw distance, dose range, field time, or machine settings. These variables are treated here as engineering proxies rather than as full substitutes for standardised uniformity metrics, and they are not pooled as if they were directly comparable CV values. Fertiliser application in Indonesian smallholder oil palm plantations is still largely conducted manually using sacks and simple spreading tools (Hidayat *et al.*, 2023; Siahaan, Wagino, & Tarigan, 2023). Although this approach can be practical and time efficient on small plots, it is often imprecise in dosage control, which may lead to inefficient fertiliser use and increased risks of environmental contamination. Several large plantation companies have begun adopting tractor-towed mechanical spreaders; however, their use remains limited among smallholders.

In countries such as India (Pawase, Nalawade, Walunj, Kadam, & Zeng, 2025), Thailand (Polwaththa, Amarasinghe, & Nandasena, 2024), and Brazil (Carballido del Rey, 2021), fertiliser mechanisation has advanced toward GPS-enabled precision spreaders and the use of drones for liquid fertiliser applications. These technologies can adjust application rates spatially according to crop needs, improve input-use efficiency and reduce environmental burdens. Compared with Indonesia, the key gaps lie in investment affordability, service support, and the still-limited use of standardised spreading pattern and uniformity testing, although substantial opportunities exist, as domestic research and interest in precision agriculture continue to expand.

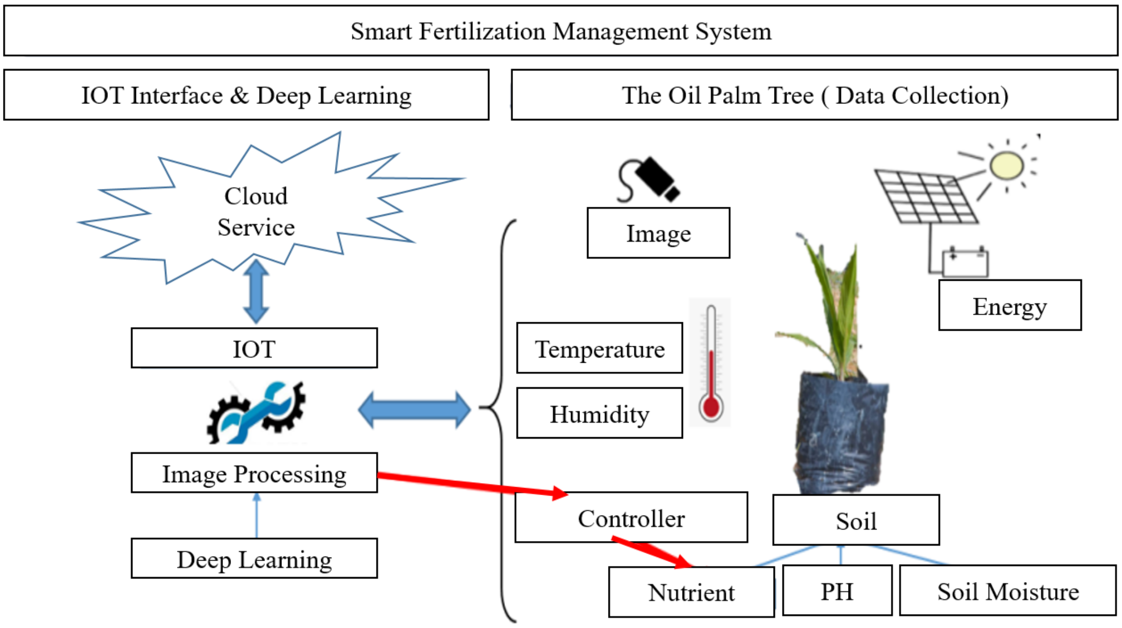


Fig. 5. Conceptual framework of smart fertilisation management system for oil palm trees (Adib & Daliman, 2021)

Several studies have begun to focus on fertiliser mechanisation to improve application accuracy and reduce fertiliser losses. Performance evaluations of tractor-towed fertiliser spreaders in mature plantations indicate that hopper settings, PTO rotational speed, and forward travel speed significantly influence distribution patterns and spreading coverage, enabling more uniform application than manual sack-based methods (Senata, 2023). For young oil palm stands, where centrifugal spreading systems can be less suitable, other work has developed pneumatic fertiliser applicators with adjustable dosing ranges of 0.25–1.5 kg per palm and a power requirement of about 0.71 kW, enabling more targeted application in immature palms without excessive overspreading (Tajalli, Hermawan, & Setiawan, 2016). More precision-oriented approaches have also emerged through fertiliser immersion, which aims to improve efficiency by placing fertiliser below the soil surface to reduce surface losses and runoff, including PTO driven implements mounted on four-wheel tractors (Kholis, 2021). Nevertheless, because most studies do not report CV, overlap patterns, or field loss fractions, the current fertiliser synthesis remains stronger on metering and placement concepts than on fully benchmarked distribution quality.

Pest and Disease Control Machinery

A more critical comparison of application architectures (ground sprayers, mist blowers/fogging, UAVs) requires consistent engineering metrics reach to tall canopies, deposition across canopy strata, drift losses, energy demand, and operator safety/exposure. Pest and disease control in Indonesian oil palm plantations is still predominantly performed using manual spraying equipment, particularly knapsack sprayers. At larger scales, gasoline powered sprayers are sometimes used; however, their deployment remains limited because of investment costs and maintenance requirements. Research attention has also tended to focus more on pesticide formulations and biological control strategies than on the engineering optimisation of application machinery.

By contrast, in Malaysia, Brazil, and other tropical commodity-producing countries, pest and disease management has increasingly adopted drone sprayers, ultra-fine fogging systems, and satellite image-based monitoring platforms. These innovations can improve pesticide-use efficiency while reducing environmental impact. A key difference relative to Indonesia is the still limited development of integrative research that links mechanised application technologies with information technology enabled pest management systems.

In Indonesia, the limited ability to reach the canopy as palms grow taller is one reason pest control still relies heavily on manual or semi-mechanised methods. A field study in North Sumatra reported that insecticide applications previously relied on knapsack sprayers and mist blowers, but have shifted toward motor sprayers and drones as palm height increases and higher application effectiveness is required (Ramadhan, Mahmudah, & Mulyani, 2024). Similar findings at the smallholder level indicate that manual knapsack sprayers require sustained pumping effort and often produce less stable spray output, making them less effective and less efficient than powered alternatives (Silalahi *et al.*, 2023). Under these conditions, advancing application-machinery innovation beyond active ingredients or IPM strategies becomes increasingly important, particularly in large areas and in terrain that restricts operator mobility.

Several Indonesian studies have pursued application of equipment designs better suited to mature oil palm. One study (Pramuhadi *et al.*, 2022) developed a mobile spray fogger to optimize pesticide fog application at specific heights. The authors highlighted that conventional operator-carried fogging is often ineffective for tall palms and that the heat from smoke can potentially damage leaves consequently, the design aimed to extend reach while reducing the risk of canopy injury. This line of work points to opportunities for more crop and context-specific application machinery (e.g. optimising fog formation, airflow direction, and tool mobility) to improve targeting to the canopy/fronds and reduce inter-operator variability in application performance.

Evidence for UAV based applications is also emerging. A study conducted at PT Langkat Nusantara Kepong compared drones with motor sprayers and found higher pest mortality using drones (88.50%) than motor sprayers (75.65%), with a statistically significant difference based on a t-test (Ramadhan *et al.*, 2024). At the industry level, drone services have also expanded toward cross border deployment; for example, a drone-based bagworm-control initiative was reported to cover 2,158 ha across Indonesia and Malaysia, emphasising application precision to reduce waste and improve efficiency relative to manual operations (Khofiyah *et al.*, 2020). These developments indicate that research on mechanised pesticide applications in Indonesia is gaining traction, yet it remains relatively disconnected from data driven monitoring and decision support systems. In Malaysia, innovation trends seem more integrative, as mechanised application is coupled with strengthened geospatial and remote-sensing-based monitoring. One report (Lye, Ahmad, Abu Hassan, & Chong, 2006; Maris, Idris, Nordiana, Izzuddin, & Norman, 2020; Mohd Najib, Kanniah, Cracknell, & Yu, 2020) describes the use of drones as a mechanisation breakthrough that supports data-driven decision-making while reducing operator exposure to chemicals.

Pruning and Canopy Management Machinery

Pruning of oil palm fronds in Indonesia is still predominantly performed manually using egrek (sickle on a pole) or dodos (chisel type) tools. While these methods can be effective in small plantations, they are less efficient at larger scales because they require substantial labour inputs. Innovations such as mechanised or hydraulically assisted egrek systems remain limited; they are more commonly tested at the trial stage and have not yet been widely adopted in practice among local communities.

As illustrated in Fig. 6, other major oil palm-producing countries, such as Malaysia, have experimented with drones to estimate the number of palms requiring pruning from image-derived spatial data (Khuzaimah *et al.*, 2022). In Brazil, hydraulically assisted pruning shears have also been adopted in cocoa and coffee plantations to improve labour efficiency. These examples suggest that Indonesia still lags in developing crop-specific technologies for oil palm pruning, although high labour demand remains one of the most critical operational challenges in the field.

Fig. 6. Spatial analysis and inventory for estimating the population of oil palm plantation trees (Khuzaimah *et al.*, 2022; Shamshiri *et al.*, 2019)

Beyond labour requirements, oil palm frond pruning is directly linked to canopy management objectives, including maintaining access along harvesting paths, removing fronds that obstruct bunch cutting, improving air circulation and light penetration, and supporting plantation sanitation. A study by Asmara, Kano, Kadir, and Suharyatun (2023) reported that mechanised cutting using a Husqvarna 327 LDx increased average output at 3 m palm height from approximately 718 to 951 fronds h^{-1}. Within the governing-process framework used in this review, that increase is interpreted primarily as a reduction in cutting cycle time per frond and as higher effective operational capacity in the pruning task. Mechanistically, the engine supplies part of the cutting energy, stabilises blade speed, and likely lowers the operator's muscular effort per cut, allowing a higher sustained work rate across the shift. Related measurements reported by (Christian, Asmara, Sugianti, & Telaumbanua, 2018) indicate energy expenditure of 2.0–5.0 kcal min^{-1} and fuel use of about 0.336 L h^{-1}, supporting the view that mechanised pruning shifts part of the task from human metabolic energy to engine power. Because the available studies do not partition cycle time, grip force, or fatigue accumulation explicitly, the causal interpretation is best stated as higher effective operational capacity with reduced operator effort as a plausible supporting mechanism rather than a fully measured causal decomposition. More recent domestic work has also focused on improving the ergonomics and performance of pole-cutting systems relevant to pruning. One study (Putra, 2024) developed an egrek equipped with an electromechanical vibrator to address the limitations of commercially available mechanised egrek systems, which have been reported to be relatively heavy (>8 kg) and limited in reach. The prototype weighed about 6.97 kg, had an optimal rotational speed of 1500 rpm, and demonstrated faster cutting times than manual operation at heights of 7–9 m.

Outside Indonesia, mechanised frond cutting and canopy management have often progressed in parallel with innovations in motorised harvesting tools. Malaysia, for instance, has developed motorised cutters that reportedly reduce workload and increase output relative to manual methods, with intended use linked to specific palm-height ranges (e.g. early generations targeted palms younger than 13 years with heights of around 5 m, while subsequent developments were reported to be effective up to approximately 7 m) (Al-Jawadiab, Ahmad, Nawi, & Kassim, 2018; Zamrosmahadi, Jie, Wessam, Faudzi, & Ahmad, 2021). Image-based approaches are also increasingly used to support pruning inventory and operational planning: detection and counting of palms from high-resolution UAV imagery can achieve high accuracy across both flat and undulating terrain, enabling block-level priority maps to guide pruning deployment (Wibowo, Sitanggang, Mushthofa, & Adrianto, 2022). Accordingly, Indonesia's gap is not limited to the cutting tool itself, but also includes the integration of spatial inventory, pruning scheduling, and mechanised cutting to enable more precise field decisions and improve labour efficiency.

Challenges and Opportunities

Engineering research needs should be stated as a gap to the solution agenda for each operation, defining the missing design rules or control algorithms, the required measurements and test protocols and the expected outputs (parameter guidelines, validated models, and scalable service-ready system architectures). Priority measurement gaps that repeatedly appear in the Indonesian literature include soil compaction (bulk density and cone index), droplet spectrum descriptors (VMD/span), wind conditioned drift, fuel versus electric energy accounting, life cycle implications, and standardised cost normalisation. Table 1 should, therefore, be read as an evidence map of what has been measured, what has only been inferred through proxies, and what remains insufficiently reported for cross-study benchmarking. An overview of relevant studies related to agricultural machinery used for field maintenance in Indonesian oil palm plantations is presented in Table 1.

Table 1- Comparative evidence map of agricultural machinery studies for field maintenance in Indonesian oil palm plantations

No	Maintenance Aspect	Author(s) (Year)	Type of Machinery	Main Findings
1	Fertiliser application (broadcast)	(Senata, 2023)	Tractor-towed fertiliser spreader + Kubota L4018 (PTO speed; hopper settings)	Max throw distance: 12 m; PTO speed affected discharged mass and distribution uniformity.
2	Fertiliser application (immature palms/TBM)	(Tajalli *et al.*, 2016)	Pneumatic applicator prototype (blower + metering)	Dose range: 0.25–1.5 kg palm^{-1}; power demand ≈0.71 kW (blower 3000 rpm); tested at 0.55 and 1.7 m s^{-1}.
3	Weed control (herbicide spraying)	(Yuliyanto *et al.*, 2017)	Manual knapsack sprayer vs motorised knapsack sprayer	Weed mortality: 90% vs 99%; total cost: IDR 34,610 ha^{-1} vs 27,241 ha^{-1} (saving 7,369 ha^{-1}); the motorised option improved spray uniformity.

4	Weed control (herbicide spraying)	(Suryanto *et al.*, 2022)	CDA sprayer (battery/dynamo + spinning disc) vs knapsack sprayer	Coverage: 1,381.6 m^2 $tank^{-1}$ (IDR 53,508 ha^{-1}) vs 188.4 m^2 $tank^{-1}$ (IDR 89,436 ha^{-1}); weed mortality: 99% vs 90%.
5	Weed control (herbicide spraying)	(Silalahi *et al.*, 2023)	Electric knapsack sprayer (electric pump)	Reported high use effectiveness (80.27%); more stable pressure; adoption influenced by extension support, field conditions, operator skills, and operating costs.
6	Pruning/canopy management	(Asmara *et al.*, 2023; Christian *et al.*, 2018)	Mechanised dodos (Husqvarna 327 LDx) vs manual dodos	Mechanised cutting increased output from about 718 to 951 fronds h^{-1} at 3 m palm height; energy expenditure: 2.0–5.0 kcal min^{-1}; fuel consumption ≈0.336 L h^{-1}.
7	Loose-fruit collection (loss reduction)	(Yuliyanto, Kuvaini, & Yogantara, 2021)	Modified loose-fruit (brondolan) collector	Labour requirement improved: 0.21 to 0.13 WD ha^{-1}; capacity: 3,346 fruits h^{-1}.
8	Infield FFB handling/evacuation	(Siregar, Nurkhoiry, Nasution, Agustira, & Amalia, 2025)	Scissor-lift grabber, quick tractor, crawler dump, mini tractor (Wintor), along-along, truck bin system	Assessed technical feasibility and reported economic metrics (NPV, IRR, B/C, payback) across multiple infield transport options.
9	Residue/biomass management	(Satya Wibangga & Sofri Ramadhani, 2021)	Oil palm fronds and leaf shredder (modified cutting system)	Chopping capacity increased: 125 to 131.43 kg h^{-1}; targeted particle size <2 cm.
10	Pest control (fogging/aerosol)	(Pramuhadi *et al.*, 2022)	Mobile spray fogger (fogging machine + electric sprayer + air blower)	Droplet diameter: 94.41 µm; droplet density: 365.44 droplets cm^{-2}; effective range: 8.63 m; effective width: 0.91 m; fog temperature reduced by ≈ 4 °C.
11	Weed control (renewable-energy sprayer)	(Pujiwara, 2022)	Solar-cell sprayer vs electric sprayer	Work rate: 0.75 vs 0.71 ha h^{-1}; operating cost: IDR 51,216.82 ha^{-1} vs 55,791.70 ha^{-1}.
12	Weed control (drone spraying)	(Mahhendra *et al.*, 2025)	Drone sprayer vs manual knapsack sprayer	Reduced spraying time by 82% and cost by 51.6% vs knapsack; no significant difference in time-to-weed-mortality.
13	Pest control (bagworm)	(Ramadhan *et al.*, 2024)	Drone sprayer vs motor sprayer	Mortality: 88.50% (drone) vs 75.65% (motor); significant difference ($p \leq 0.05$).
14	Weed control (boom sprayer operations)	(Sihombing, 2025)	Boom sprayer (MKTI operations)	Operational study documenting implementation workflow, resource requirements, and work practices for boom-sprayer-based herbicide application.
15	Weed control (CDA/ULV)	(Purnama, Dalimunthe, Septyani, & Sepriani, 2023)	CDA unit (Micron Herbi) for ULV (<50 L ha^{-1}) + glyphosate	Weed mortality after application: 10% (10 d), 40% (20 d), 100% (30 d); demonstrates ULV application using a commercial CDA system.

16	Fertiliser application (subsurface placement)	(Kholis, 2021)	PTO-driven rotary fertiliser-immersion implement (3-point hitch)	Placement depth: 10–15 cm; dose ≈1 kg m^{-1}; rotary unit: 20 cm working width at 200 rpm.
17	Fertiliser application (immersion field trial)	(Arief, 2020)	Fertiliser-immersion machine (prototype; plantation trial)	Field performance: 6.8 h ha^{-1}; diesel use: 43 L ha^{-1}; intended to improve dosage accuracy and application timeliness vs surface broadcasting.
18	Replanting (stem felling & shredding)	(Mahfud, 2020)	Bucket mulcher attachment	Best operating method: Push Tree; capacity: 141.26 kg min^{-1}; fuel use: 6.02 L $palm^{-1}$.
19	Soil moisture/conservation	(Alfarisi, Sutejo, & Mandang, 2021)	Oil palm stem mulch (mulcher output) as soil conditioner	Mulch thickness 10 cm performed best: soil moisture 28.22%; penetration resistance 15.13 kgf cm^{-2}; soil temperature 27.5°C.
20	Loose-fruit collection (automation)	(Putra, Finawan, Rusli, & Mauliza, 2024)	Arduino Uno-based loose-fruit collector prototype (joystick control)	Prototype designed to collect scattered loose fruits and transfer them into a container; focus on automation and improved ergonomics.

Notes: TBM = immature/non-bearing palms; FFB = fresh fruit bunches; WD = workday; CDA = controlled droplet application; ULV = ultra-low volume

To complement Table 1, a comparative performance evidence map is presented in Table 2 to summarise the relative strengths, limitations, and reporting completeness of the main field maintenance technologies discussed in this review. Because the included studies reported performance using heterogeneous metrics and levels of detail, Table 2 should be interpreted as a structured cross-study synthesis rather than a fully normalised benchmark comparison.

Table 2- Comparative performance evidence map of field maintenance technologies in Indonesian oil palm plantations

Technology	Main task	Operational capacity	Process quality/output consistency	Task effectiveness	Energy/fuel demand	Cost efficiency	Operator burden/exposure	Terrain adaptability	Evidence completeness
Manual knapsack sprayer	Weed control	Low–medium	Low–medium	Medium	Low	Medium	High burden	High	Medium
Motorised knapsack sprayer	Weed control	Medium	Medium	Medium–high	Medium	Medium–high	Medium	High	Medium
CDA sprayer	Weed control	Medium–high	High	High	Low–medium	High	Medium–low	Medium–high	Limited–medium
Drone sprayer	Weed/pest control	High	Medium–high	High	Medium	Medium–high	Low burden	Medium–high	Limited
Tractor-towed fertiliser spreader	Fertiliser application	High	Medium	Medium–high	High	High on larger blocks	Low	Low–medium	Limited
Pneumatic fertiliser applicator	Fertiliser application	High	High	High	Medium	Medium–high	Low	Medium	Limited
Fertiliser immersion machine	Fertiliser placement	Medium	Medium	Medium	Medium	Medium	Medium	Low–medium	Limited
Mechanised dodos	Pruning/frond cutting	High	Medium–high	High	Medium	Medium–high	Medium–low	Medium	Limited
Vibrating egrek prototype	Pruning/harvesting support	Medium	Medium	Medium	Medium	Not yet established	Medium	Medium	Limited

Note. Relative ratings are intended as a structured synthesis of the reviewed evidence and not as a fully standardised benchmark. “Limited” indicates that the technology appears promising, but the available Indonesian evidence is sparse, prototype-based, or lacks complete reporting of standardised engineering metrics.

The main value of Table 2 is not to claim full equivalence among technologies, but to make explicit where the current Indonesian evidence is strong, weak, or incomplete. In particular, the table shows that operational performance is discussed more often than application quality indicators, while deposition, drift, and standardised energy metrics remain underreported. This pattern helps explain why several technologies appear promising in practice but are still difficult to compare rigorously across studies. Building on this comparative evidence map, the following section synthesises the main engineering trade-offs and research gaps across weed control, fertiliser application, pest and disease management, and pruning/canopy operations.

Cross-Study Evidence Synthesis

Across the 20 included studies, quantitative reporting is densest for spraying systems. Weed-control studies reported work rates of 0.71–0.75 ha h^{-1} for electric/solar knapsack sprayers, coverage per tank of 188.4–1,381.6 m^2 for knapsacks versus CDA, and cost reductions from IDR 89,436 to 53,508 ha^{-1} for CDA and 51.6% for drone spraying relative to knapsack baselines. Fertiliser studies reported throw distance up to 12 m, dosing capacity of 0.25–1.5 kg $palm^{-1}$, and field performance of 6.8 h ha^{-1} for subsurface placement. Pruning studies reported 718–951 fronds h^{-1} with mechanised cutting at 3 m palm height and fuel use around 0.336 L h^{-1}. However, standardised CV, VMD, deposition, drift, and operator exposure metrics remain sparse, so these evidence ranges should be interpreted as indicative rather than exhaustive. Table 1 functions most robustly as a comparative evidence map rather than as a fully standardised benchmark table.

The principal constraints in developing maintenance machinery for oil palm plantations in Indonesia can be grouped into three interacting layers: (i) technical fit, including terrain, palm geometry, road access, and machine maintainability; (ii) service ecosystem, including spare parts, workshop access, and trained operators; and (iii) investment structure, including high upfront costs and the predominance of smallholder plantations (Santoso *et al.*, 2025). This framing helps explain why technically promising machines often remain confined to trials or estate-level implementation rather than diffusing widely.

Despite these constraints, the development potential remains substantial. Global trends toward precision agriculture, the growing prominence of oil palm sustainability initiatives (ISPO/RSPO), and government efforts to enhance smallholder productivity can collectively serve as strategic entry points for advancing maintenance mechanisation. The strongest opportunities lie in technologies that combine technical robustness with service-based deployment models, operator training, and maintainable designs realistic for heterogeneous Indonesian field conditions.

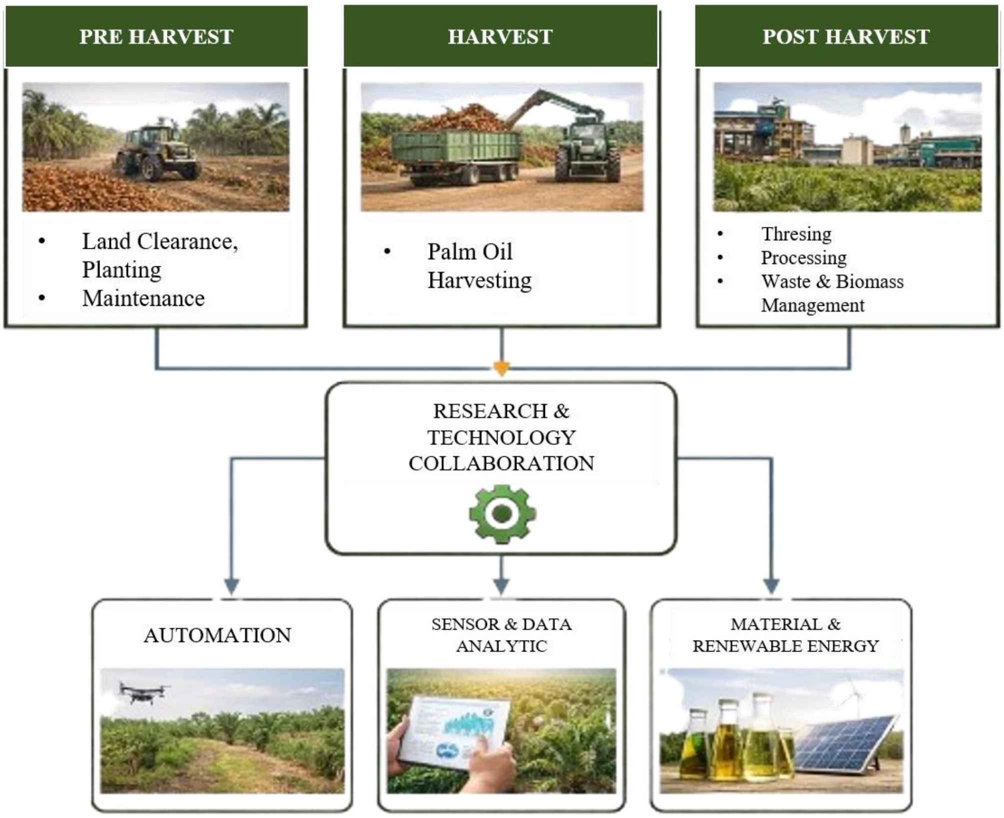


Fig. 7. Research map of oil palm agricultural machinery

Implications for Future Research

Oil palm plantations represent a high-risk enterprise in which inadequate management can lead to substantial financial losses. Large land areas, significant capital requirements, and the diversity of maintenance operations, including weed control, fertilisation, pest and disease management, soil and water conservation, and canopy pruning, collectively demand adequate mechanisation support. In practice, however, deploying different agricultural machines and implements for each maintenance operation often imposes a heavy cost burden, particularly for smallholders with limited capital. This situation indicates that conventional mechanisation systems based on single purpose machinery are poorly aligned with the characteristics of oil palm production in Indonesia.

As an alternative, the concept of modular agricultural machinery should be advanced as a key direction for future research. Under this concept, a single base unit can be configured with interchangeable implements or modules tailored to field requirements, such as spraying, pruning, fertilisation, and weed-control modules. A modular approach has the potential not only to reduce investment and maintenance costs but also to enhance operational flexibility, efficiency, and machine adaptability to the heterogeneous conditions of smallholder plantations (Santoso *et al.*, 2025). Subsequent research should focus on developing a comprehensive framework that integrates technical dimensions (modular mechanical design, sensor integration, and AI-enabled functions), economic considerations (business feasibility and cost-benefit analysis), and social factors (farmer acceptance and usability), with service-based deployment and maintenance models that make advanced equipment accessible beyond large estates. In this way, a modularisation framework could provide a foundation for more inclusive, affordable, and sustainable oil palm mechanisation innovations in Indonesia.

Fig. 8. Conceptual framework of modular agricultural machinery for oil palm field maintenance

Conclusion

This integrative review shows that field maintenance mechanisation in Indonesian oil palm plantations is advancing, yet uptake remains limited by high investment costs, restricted equipment access, and low adaptability to heterogeneous smallholder conditions. Across weed control, fertilisation, pest/disease management, and pruning, the evidence suggests that improving operational efficiency and sustainability will require technologies that are affordable, flexible, and scalable. At the same time, the current evidence base remains measurement-sparse: only a minority of studies report standardised engineering metrics such as CV, VMD, on target deposition, drift, energy per hectare, or operator exposure. We therefore highlight modular agricultural machinery and standardised test/reporting protocols as priority directions so future Indonesian studies can generate transferable design rules, stronger cross study benchmarking, and more robust decision support.

Acknowledgements

The authors gratefully acknowledge the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia for financial support through the Doctoral Education Programme Scholarship for Indonesian Lecturers (Programme Pendidikan Doktor untuk Dosen Indonesia, PDDI) 2025 (Award/Grant No. 000663/PPAPT.1.2/BPI.06/08/2025).

Conflicts of interest

The authors declare no conflict of interest.

Data availability

No new experimental data were generated for this study. All evidence synthesised in this review was extracted from published sources cited in the manuscript.

Declaration of generative AI and AI assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used ChatGPT (OpenAI) and Paperpal to improve language clarity, readability, and grammar**.** After using these tools/services, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Author Contributions

D. Santoso: Conceptualisation, Methodology, Technical advice, Data acquisition, Data pre- and post-processing, Software services, Visualisation

I. Iqbal: Supervision, Validation, Review and editing services

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مقاله مروری

مرور مبتنی بر علوم مهندسی از ماشین های داشت مورد استفاده در مزارع نخل روغنی اندونزی: معیارهای عملکردی، فرآیندهای حاکم و نیازهای تحقیقاتی

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تاریخ دریافت: ۱۴۰۴/۱۱/۲۴
تاریخ پذیرش: ۱۴۰۵/۰۱/۲۹

چکیده

نخل روغنی از اقتصاد روستایی اندونزی پشتیبانی می‌کند، با این حال عملیات نگهداری مزرعه همچنان نیاز شدید به نیروی کار دارد و اندازه‌گیری کمی در این زمینه انجام شده است. این مرور مبتنی بر علوم مهندسی، ۲۰ مطالعه منتشرشده در سال‌های ۲۰۱۵ تا ۲۰۲۵ در مورد کنترل علف‌های هرز، کاربرد کود، مدیریت آفات و بیماری‌ها، هرس/کار بر روی سایبان درخت و پشتیبانی از عملیات خاک/بقایا در نخل روغنی اندونزی را بررسی می‌کند. برای رسیدگی به گزارش‌های ناهمگن، شاخص‌های عملکرد به‌عنوان معیارهای گزارش‌شده مستقیم، معیارهای به‌دست‌آمده، شاخص‌های پروکسی یا گزارش‌نشده طبقه‌بندی شدند. هیچ مقدار از دست رفته‌ای برای توصیف‌گرهای ضریب تغییرات، نشست، بادبردگی یا توصیف قطرات در نظر گرفته نشد. بر اساس شواهد موجود، سمپاش‌های برقی/موتوری، سیستم‌های CDA و سمپاشی با پهپاد عموما زمان و یا هزینه را نسبت به روش دستی کوله‌پشتی کاهش دادند، در حالی‌که پخش‌کننده‌های پشت تراکتور، دستگاه‌های پنوماتیک و جایگذاری زیرسطحی، دوز و اعمال هدفمند را در عملیات کوددهی بهبود بخشیدند. با این حال، تنها تعداد کمی از مطالعات، معیارهای مهندسی استاندارد مانند CV، VMD، نشست روی هدف، بادبردگی یا قرار گرفتن اپراتور در معرض کود را گزارش کردند. این بررسی به‌جای یک متاآنالیز رسمی، یک مقایسه مهندسی ساختاریافته را ارائه می‌دهد و نیازهای تحقیقاتی اولویت‌دار را شناسایی می‌کند: پروتکل‌های استاندارد آزمایش، گزارش‌دهی معیارهای قابل‌مقایسه و پلتفرم‌های چندمنظوره مدولار یکپارچه با مدل‌های حسگری، پشتیبانی تصمیم‌گیری و استقرار مبتنی بر خدمات.

واژه‌های کلیدی: کشاورزی دقیق، ماشین های داشت، مفاهیم مدولار، نگهداری مزرعه، نخل روغنی

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https://doi.org/10.22067/jam.2026.97821.1472