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LEGUMINOUS COVER CROPS IN MALAYSIAN OIL PALM FIELDS: THE SPECIES, SEED TECHNOLOGY, FIELD PRACTICES AND FUTURE TRENDS

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ABSTRACT

Leguminous cover crops (LCCs) in Malaysian oil palm fields are a living mulch with multiple benefits. The roots have a symbiotic association with rhizobia, which fix atmospheric nitrogen (N), promoting the growth and development of oil palms at reduced N fertilisation. The creeping vines and their leaves conserve soil moisture, regulate soil temperature, add organic matter, control erosion and manage weeds. This article deliberates a review on the choice of LCCs, seed availability, seed quality and scarification techniques practiced among Malaysian planters. The application of seed technology in extending the shelf life of seeds is presented to support consolidated shipments. Some cost-effective fertilisation techniques are also mentioned for facilitating the ground cover by LCCs in the oil palm fields. As more consideration is paid to the oil palm production systems in Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO) certification to meet the market needs, this review is hoped to encourage the cultivation of LCCs among planters who have yet to gain benefits from these ground cover plants while reducing synthetic fertiliser inputs, nitrate leaching and carbon footprint in the production of this economically important crop.

Keywords: quality, scarification, seed, sustainability, weed.

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INTRODUCTION

In many Malaysian oil palm estates, the cultivation of leguminous cover crops (LCCs) as non-cash crops in the interrows has been one of the sustainable practices for decades. These creepers are planted in the fields before or together with the oil palm seedlings to keep the ground covered as long as possible. With their extensive vines, LCCs serve as a living mat that suppresses the weeds following reduced light availability for the growth of the seedlings of weeds (Kocira *et al*., 2020; Tambunan *et al*., 2017). At the same time, LCCs conserve soil temperature and moisture (Salako & Tian, 2003). Likewise, LCCs are also effective for controlling runoff and soil erosion, especially on terraces and slopes, as their root systems hold the soil particles well (*Figure 1*) (Perron *et al*., 2024).

Besides ground protection benefits, LCCs are capable of fixing atmospheric nitrogen (N) for crop nutrition in symbiosis with rhizobia (Pipai *et al*., 2023; Sulok *et al*., 2014; Swarnalakshmi *et al*., 2020). The roots of the cover crops form nodules that host the bacteria and enhance N availability for the crops and later increase N in soils, following the mineralisation of the dead biomass (Yang *et al*., 2019). Depending on the soil condition, the immature and mature oil palms need substantial annual N inputs of approximately 50-90 and 150-200 kg N/ha, respectively, while the presence of LCCs provides up to 250 kg N/ha/yr, depending on soil type, allowing for reduced chemical N fertilisation and reducing carbon footprint in the palm oil production (Chang *et al*., 2022; Clermont-Dauphin *et al*., 2016; Pardon *et al*., 2016). Such N management in oil palm is not only cost-effective but also environmentally sound when the associated issues of rapid denitrification and volatilisation from chemical N compounds, as well as eutrophication of water bodies following nitrate runoff and leaching, are reduced. Furthermore, the biomass deposited onto the soil as some fractions

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of LCCs that died, will modify the bulk density of the soil, and improve the structural and water-holding capacity of the soil (*Figure 1*) (Yang *et al*., 2023). A cascade of soil chemical and physical property enhancement will ultimately support the population of soil dwellers, especially the growth of beneficial microorganisms, which mobilise the phosphorus and other elements essential for oil palms.

Along with the yielding oil palms, LCCs are nutritious forages providing high-quality proteins to the ruminants in the oil palm-livestock integration (Friday *et al*., 1999). However, it is advisable to control the grazing of the animals to sustain the benefits of LCCs around the oil palms. On the other hand, the LCC vines that start climbing the oil palms and get entangled in the fronds of the palms can be cut off for silage.

Despite the mutualistic relationships between LCCs and oil palms, not all oil palm plantations in Malaysia are planted with LCCs. Among the 5.65 million hectares of land cultivated with oil palms in this country, about 83% belongs to large companies (Senawi *et al*., 2019; Statista Research Department, 2024). These large companies are mostly committed to Roundtable on Sustainable Palm Oil (RSPO), as well as the locally adapted Malaysian Sustainable Palm Oil (MSPO) certifications in oil palm productions with LCC cultivation included in their sustainability policy. The remaining area is managed by smallholders having less than 100 acres or 40.46 ha each. Unlike large companies, many smallholders are unwilling to spend extra money on LCCs, although their fields are also MSPO certified. It could be attributed to the lower level of awareness of LCC planting, limited roadshows and publications on LCC planting and its related improved techniques applicable in Malaysia. As we promote sustainability in oil palm production, this review presents the LCC cultivation in Malaysian oil palm fields, as well as the issues related to the supply of quality seeds and innovative practices that enhance speedy ground cover in the fields, intending to stimulate thoughts that further improve LCC-oil palm associations. While several selected LCC species have remained the primary choices for decades, this paper highlights the applications of scarified seeds in ensuring uniform germination in the fields. With the experiences gained through some collaborative work, some innovative field techniques that enhanced ground cover by LCCs are also described. Lastly, this article suggests some future seed technology and oil palm-LCC agronomy to promote LCC adoptions in all oil palm fields.

LEGUMINOUS COVER CROP (LLC) SPECIES

Being a perennial in complement to oil palm, LCC should be a fast-expanding creeper that produces a large amount of biomass for positive impact as ground cover within the shortest period. Over the past few decades, Malaysian plantations have adopted several selected LCC species based on their morphological features and physiology for tropical climatic conditions (Othman *et al*., 2012). The height or upright growth of different LCCs, their internodal length, leaf area or size and the apical, as well as the axillary growth from the vines, are species-specific, while they also show different tolerance to shading imposed by the maturing oil palms and have varying resistance to low rainfall. Thus, some planters introduce two to three LCC species in their fields in the hope of preserving the ground cover even beneath the mature trees. A few commonly cultivated LCCs in Malaysian plantations are described below.

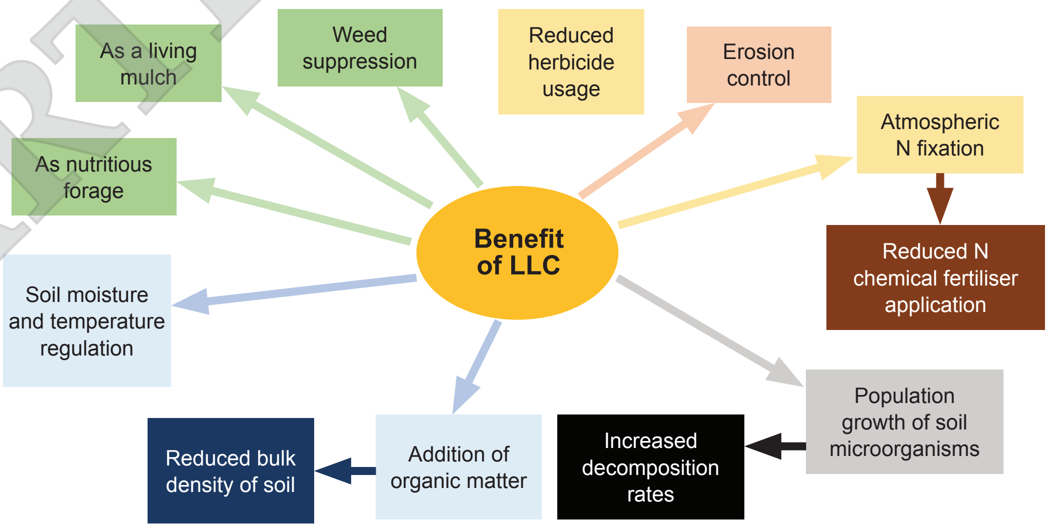

Figure 1. The benefits of leguminous cover crops (LCCs) in plantations.

Pueraria phaseoloides (Roxb.) Benth.

Pueraria phaseoloides is a vigorous LCC with trifoliate leaves. Each leaflet is large, with a length of up to 20 cm, hairy and triangular to ovate-shaped. It also has long internodes of 5-11 cm (Halim, 1997). Its stolons root at the nodes when in contact with soil. It allows for the formation of a living mat (*Figure 2a*). This LCC usually provides a thick ground shield of about 60 cm and achieves up to 70% coverage after approximately four months, depending on the soil type (*Table 1*). Thus, it is commonly seen covering the site totally among the standing young oil palms within eight months. Past studies reported that this LCC could produce about 8-10 t of biomass/ha annually, illustrating that it is a suitable choice for rapid ground protection and control of weeds on the oil palm sites (Clermont-Dauphin *et al*., 2016; Dinesh *et al*., 2004). In addition, this LCC has a deep-root system and is water-logging tolerant, and thus, it is also an excellent candidate for the low-lying areas that are prone to flood following prolonged rain. In the plantations integrated with cattle, it is a palatable pasture legume (Grinnell *et al*., 2022).

The inflorescence of this LCC is a raceme bearing purple coloured flowers. With successful pollination, pods about 10 cm long are formed, which turn black when ripe. There are 10-20 brown coloured seeds in each pod. The seeds are small, measuring only 2-3 mm.

Pueraria phaseoloides climbs the young oil palms after complete ground coverage. The common practice to prevent the overshading of palms includes manual and mechanical clearing of this LCC around the palm. In large-area estates, the application of selective herbicides as circular weeding is more cost-effective for controlling the spread of this LCC onto the fronds.

To expedite nodulation and atmospheric N fixation in the roots, planters usually mix the seeds with *Rhizobium* inoculants for field sowing. Rhizobia inoculants could increase 60%-70% N yield in *P. phaseoloides* compared to the non-inoculated plants (Sylvester-Bradley *et al*., 1991). Then, this LCC can be a supplement to the palms for approximately three years since it is rather shade-tolerant. When it dies off, the biomass contributes a marked increase in the growth and yield of oil palm following mineralisation of the biomass (Perron *et al*., 2022).

Botanically, *P. phaseoloides* has several varieties. *Pueraria phaseoloides* var. *javanica* (Benth.) Baker [synonym: *Pueraria javanica* (Benth.) Benth.] is the variety widely cultivated in the Malaysian oil palm areas and also other plantations of rubber and coconut. It can be planted as a single LCC or in a mixture with other LCCs in the plantations.

Calopogonium mucunoides Desv.

Calopogonium mucunoides has vegetative morphometrics rather similar to those of *P. phaseoloides*, but both the leaves and stems of *C. mucunoides* have long spreading ferruginous hairs, making it less palatable to cattle (*Figure 2b*). The inflorescence is also a raceme with purple coloured flowers, but the fruits are shorter pods of 2-4 cm. Each pod has 3-8 light brown coloured seeds (Peng & Aminah, 1997).

Calopogonium mucunoides is also a fast-growing LCC, gaining biomass of approximately 4 t/ha annually (Dinesh *et al*., 2004). Moreover, it nodulates indiscriminately with indigenous rhizobia; The seeds are usually sown without the addition of *Rhizobium* inoculants. For the rather acidic sites with pH in the range of 4.0-4.5, *C. mucunoides* thrives better in comparison with other LCC species, while fertilising the acidic soils with dolomite boosts its growth and biomass production. Nevertheless, *C. mucunoides* is poorly adapted to shade. Therefore, it is usually sown in a mixture with other LCCs, for example *P. phaseoloides*.

Calopogonium caeruleum (Benth.) C. Wright

Calopogonium caeruleum is another perennial *Calopogonium* planted with oil palm. Its less hairy or hairless above-ground leaves and stems set it apart from *C. mucunoides*. In addition, it becomes woody with age.

Calopogonium caeruleum has slower initial growth rates, but it tolerates drought and heavy shade well (Tan *et al*., 1976). Thus, it is suitable as a mixture with *P. phaseoloides* or *C. mucunoides* in LCC planting programs to provide quantitative and qualitative benefits collectively to immature and mature oil palms for extended periods (*Table 1*).

Centrosema pubescens Benth.

Centrosema pubescens is another LCC with a slow initial growth rate. The leaves are also trifoliate, but the leaflets are ovate-oblong. Its axillary racemes consist of pale violet coloured flowers. Each flower yields a dark brown pod up to 15 cm long, containing up to 20 dark brown spherical seeds of about 4 mm in diameter (Teitzel & Peng, 1997).

Like *C. caeruleum*, it is shade-tolerant and turns woody after 18 months (*Table 1*). It persists for up to six years under the closing canopy of oil palms or other plantation crops. Thus, it is also usually mixed with the fast-growing *P. javanica* and *C. mucunoides* in the field introduction of LCCs.

For the livestock-oil palm integrated estates, *C. pubescens* is forage suitable for the cattle. It is also a source of protein for broiler chickens.

***Mucuna bracteata* DC. Ex. Kurz**

Mucuna bracteata was brought into Malaysia from India in 1991, and was widely cultivated in many large estates of rubber and oil palm (Mathews, 1998). Morphologically, the leaves are also trifoliate, and the leaflets of approximately 6 x 12 cm are obliquely ovate or triangular. In the tropical region, this LCC thrives with vegetative parts and does not flower (*Figure 2c*). It has been reported to flower only in colder environments. Its racemes bear blackish-purple flowers that emit a stinking smell to attract insect pollinators (Wilmot-Dear, 2008). Fruits are pods covered by stinging and sharp needle-like hairs, becoming black in colour when ripe. Each pod contains 4-5 seeds. The seed is large, measuring about 1 cm in length. It is barrel-shaped, having the hilum seen in the middle of the concave side.

Mucuna bracteata has been proven more effective than the conventional LCCs in biomass production ascribed by its rapid growth, forming a thick layer of foliage of >50 cm off the ground (Chathurika *et al*., 2010; Chiu & Bisad, 2006; Sakiah *et al*., 2018). It smothers the weeds with not only the shade created by the leaves but also the growth inhibition effects on the weeds through allelopathy. When introduced in a mixture with other LCCs, *M. bracteata* eventually suppresses the other LCCs and colonises the site. Other desirable characteristics of *M. bracteata* include shade and drought tolerance (*Table 1*). This LCC has exhibited its ability to thrive even beneath the 10-yr oil palm canopy. In terms of susceptibility to pests and diseases, this LCC has a higher amount of phenolic acids, which impede many pests and disease-causal agents. Likewise, this LCC controls certain insect pests and pathogens of oil palms. Within the soil, the robust and deep tap roots and the extensive lateral roots make *M. bracteata* superior to other LCC species for erosion control, especially as contour strips on terraces, while also regulating N in its plant parts through atmospheric N fixation in the nodules (Koutika *et al*., 2001; Mishra *et al*., 2023; Wawan *et al*., 2019). However, the very aggressive climbing vines can hamper a positive association with the main crops, especially in young oil palms, as the vines cover the crowns and reduce the light penetration for optimal growth of the young trees. Thus, the management of the fast-expanding vines poses a significant impact on labour needs. With time, this problem has been resolved with periodic circular weeding around the palm stems using some suitable herbicides.

SEED QUALITY

LCCs are generally established in the field through direct seeding, while some planters raise *M. bracteata* seedlings in the nursery before field planting of this LCC species. Thus, the availability of quality seeds is a prerequisite for cost-effective LCC introduction in oil palm plantations. In general, high-quality seeds ensure good sprouting, early seedling development, and speedy ground cover with minimal care (Afzal *et al*., 2020; Runck *et al*., 2020; Spielman & Kennedy, 2016). Geographic distribution, soil quality and fruit maturity affect the development and quality of seeds. LCC seed quality is also reliant on appropriate postharvest handling and distribution channels for the benefit of the plantation crops.

Morphological Determinants

Seed size as an evolutionary trait and physiological quality is among the prime considerations in assessing the potential performance of any seed batch. As a rule of thumb, larger seeds with more nutritive reserves are desirable as bet-hedging against the unpredictable field environment (Smitchger & Weeden, 2018; Souza & Fagundes, 2014; Steiner *et al*., 2019). Large *M. bracteata* seeds, for example, produce more vigorous seedlings, favouring biomass production,

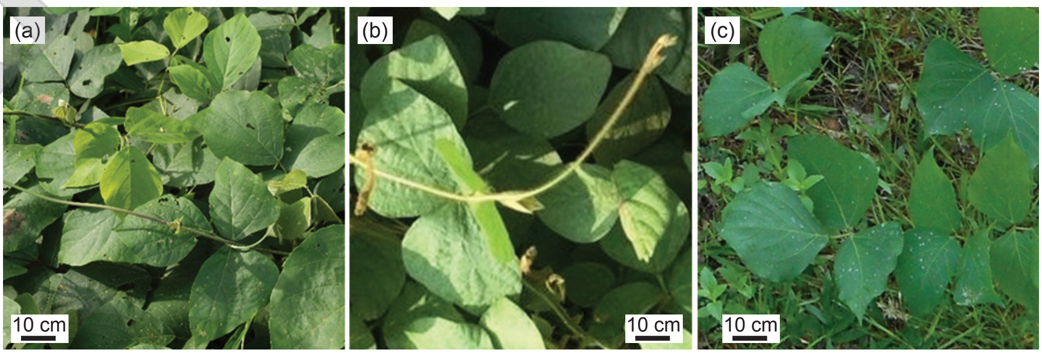

Figure 2. Leguminous cover crops (LCCs) commonly seen in Malaysian oil palm fields; (a) Pueraria phaseoloides *var.* javanica, *(b)* Calopogonium mucunoides *with conspicuous hairs and (c)* Mucuna bracteata *apical vine having silvery green leaflets.*

TABLE 1. SUMMARY OF LCC DESCRIPTIONS

LCC	Growth rate	Water logging tolerance	Drought tolerance	Shade tolerance	Forage (F)/ silage (S)	As single LCC (S)/ in mixture with other LCC (M)	Reference
Pueraria phaseoloides	Rapid growth	Good	Poor	Good	F, S	S, M	Halim (1997); Dinesh *et al.* (2004); Clermont-Dauphin *et al.* (2016); Grinnell *et al.* (2022)
Calopogonium mucunoides	Rapid growth	Poor	Poor	Poor	S	M	Peng and Aminah (1997); Dinesh *et al.* (2004)
Calopogonium caeruleum	Slow growth at the initial stage	Poor	Excellent	Excellent	--	M	Tan *et al.* (1976)
Centrosema pubescens	Slow growth at the initial stage	Poor	Excellent	Excellent	F, S	M	Teitzel and Peng (1997)
Mucuna bracteata	Apical dominance at the initial stage; aggressive growth after 1 yr	Poor	Excellent	Excellent	S	S, M	Mathews (1998); Chiu and Bisad (2006); Wilmot-Dear (2008); Chathurika *et al.* (2010); Sakiah *et al.* (2018)

N fixation rate and weed suppression, especially for direct field seeding in oil palm fields (*Figure 3*) (Tsan *et al.*, n.d.). In contrast, small and dented seeds within the same seed lot could be indicative of lower energetic value or even pest infestations. These inferior seeds usually have asynchronous sprouting and heterogenous germination time, and develop smaller and weaker seedlings, being susceptible to harsh field conditions.

Another visual indicator for the germinability of LCC seeds is the seed coat colour. Regardless of loci and genetic factors, seed colour is frequently associated with the maturity stage, as well as environmental stimuli, affecting the sprouting capability of the seeds with some exceptions (Bhatt *et al.*, 2016; Sujatha *et al.*, 2022; Velijević *et al.*, 2017; Zhang *et al.*, 2013). For example, oil palm seeds of varying colours are linked to the pigmentation factors without compromising their germination capacity and seedling growth (Norsazwan *et al.*, 2022). For the LCC seeds, seeds of bright colour usually demonstrate a good sprouting rate and are sought after by the buyers. Off coloured legume seeds are usually low-quality seeds (Anuradha *et al.*, 2009). In most cases, *C. mucunoides* seeds of light brown colour can have an above 90% germination rate, but the black coloured seeds usually show below 20% germination (*Figure 4*) (Tsan *et al.*, n.d.). At postharvest, seed colour changes can be indicative of certain chemical or pigment changes and the consequence of seed aging (Zhang *et al.*, 2013, 2021). *M. bracteata* seeds with dull appearance following prolonged or improper storage are distinguishable from the bright, shining seeds in terms of reduced germination rate (*Figure 3*). However, separating the dull coloured seeds from the bright coloured seeds can be challenging; both the manual method or even a seed colour sorter may not efficiently sort out the undesirable dull coloured seeds.

Figure 3. Mucuna bracteata *seeds of different sizes and colours. Dented seeds (in blue circles) and small seeds (in red circle) are low-quality seeds with delayed germination and they develop small seedlings.*

Figure 4. Calopogonium mucunoides *seeds of different colours. Bright brown (BB) and brown (B) coloured seeds have high germination rates of up to 90%, while dark brown (DB) and black (Bl) coloured seeds have low germination rates of below 20%.*

Supply Chain Factor

In Malaysia, LCC seeds are mostly imported from the neighbouring countries of Indonesia and Thailand, while some seeds are brought in from India (Tsan *et al*., n.d.). Locals supply only small quantities of seeds. In general, there is a complex dynamic within the distribution network of seeds where inspections and quality control can be overlooked (Gerrano *et al*., 2022). Moreover, the seeds deteriorate along the supply chain (Barriga & Fiala, 2020). In the case of LCC distribution, the above issues can be exaggerated with mishandling and poor packaging, as LCC seeds are not high-value seeds. At a marginal price of seed procurement at the present state, LCC seeds are often packed with a fungicide as a law and custom requirement, and the treated seeds are placed in two-layer polyethylene bags or paper bags protected by an external layer of polyethylene bag each. Upon request, the seed trading company provides a basic seed germination test report. With these limitations in mind, the quality of LCC seeds delivered to Malaysia is sometimes compromised and local seed-supplying companies employ a compensation scheme to provide assurance of seed performance as a competitive marketing strategy.

Seed Storage Effect

After bulk purchases for continuous local market needs, as well as a cost-saving seed acquisition measure, the LCC seeds may need to be stored for a year or more before sowing. In general, LCC seeds are durable ascribed to the thick seed coat like many other seeds with a thick covering (Mattana *et al*., 2022). The attached seed germination test report is another valuable specification in predicting the storability of the seeds. When received at a safe moisture content of about 10%, the intact seeds are impermeable to moisture and gases and remain physiologically inactive. Over a prolonged time with perforated storage in Malaysian premises, the seeds may be prone to gradual seed coat degradation allowing for the migration of moisture from the atmosphere into the seeds, increasing the water potential gradient of the seeds resulting in an increased metabolic rate and heat release from the respiring seeds, as typically shown by aging seeds left in the hot and humid tropical environment (Afzal *et al*., 2020; Rehmani *et al*., 2023). This will exaggerate seed aging, leading to mortality and loss if not sown. On the other hand, the bulky LCC seed stock will not be stored under ideal dry and cool conditions to arrest the metabolic activities in seeds and preserve seed longevity due to cost factors. Thus, good coordination of short- and long-term procurement programmes play a key role in the quality assurance of LCC seeds for the benefit of oil palms.

SEED GERMINATION

Succeeding LCC seed acquisition, a high percentage of germination and vigorous growth of the seedlings are desirable. Naturally, the thick coat of LCC seeds hinders water uptake or imbibition and inhibits gas exchange. In other words, these seeds are hard seeds that impose physical dormancy. The seed coat must be modified for the quiescent seeds to receive water and oxygen before they resume the physiological processes and cellular growth into photosynthetic seedlings (Baskin & Baskin, 2020).

Seed Scarification

Like many seeds enclosed within a hard coat, germination of LCC seeds generally commences after soaking the seeds in hot water or treatment with acid that weakens the seed coat integrity (Ardiarini *et al*., 2021; Department of Standards Malaysia, 2004; Han *et al*., 2022; Yang *et al*., 2022). Likewise, any mechanical abrasion and rubbing that reduce the seed coat thickness will provide a similar positive effect that initiates seed germination. The procedures that result in controlled seed coat impairment are collectively termed scarification. The document that indicates the growth potential of any shipped LCC seeds is a germination rate report after performing a selected scarification procedure, while the shipped seeds are non-scarified seeds that remain dormant until they are needed to germinate later.

Marketing of Scarified Seed

The necessity to reduce the seed coat thickness to initiate early germination creates new business opportunities among local LCC seed traders. Scarified seeds of many crops are gaining popularity among farmers nowadays for guaranteed seed germination rates in the fields, despite being more expensive than intact seeds (Pedrini *et al*., 2017). In the production of such value-added seeds, the seeds are unvaryingly abraded within specially designed drums, granting rapid and uniform germination. To endure mechanical abrasion, LCC pods must be harvested at the fully ripe stage, in which the seeds have a low moisture content of about 12%. Otherwise, the seeds are spread on the ground for sun-drying at postharvest as a low-cost method to lower the seed moisture content and ascertain tolerance to mechanical scarification of the seeds.

The sufficiently abraded commercial seeds become a reliable solution in LCC field establishment amidst labour shortage. Without the ready-to-germinate seeds, manual clipping, for example, in handling *M. bracteata* seeds, is very labourious. Simultaneously, the low-cost hot water soaking procedure is effective only when working with small batches of seeds so that all seeds receive the right temperature treatment to weaken the seed coat. In light of the inconveniences, the planters turn to accessible scarified seeds to consolidate simplicity and efficiencies for earlier field cover with LCCs.

With a thinner seed coat, the scarified seeds are theoretically less storable than the unprocessed seeds. Conventional packing and storage of these processed seeds in perforated gunny sacks, paper bags, or polyethylene bags under tropical climatic conditions will result in progressive spoilage of the seeds over time as the relatively higher temperature and humidity collectively drive the increased cellular metabolism, leading to seed aging. In addition, the seeds with thinner seed coats also face a higher potential of insect pest damage with conventional packaging and storage. While protecting the processed seeds from deterioration is necessary, other options are sought after in prolonging the shelf life of these seeds. Following the large-scale mechanical abrasion of seeds for cost-effectiveness, the processed seeds are currently found to be best stored in hermatic ziplock packs or with vacuum packaging that creates a resource-depleted environment to preserve the seeds.

FIELD PLANTING

LCCs are generally introduced in fields after land clearing and lining for oil palms. The efficacy of LCCs in supporting ecologically sound and sustainable crop production is a function of a broad range of factors. These factors, solely or in combination, affect the services of LCCs in plantations. As a general rule, early and uniform sprouting and high rates of germination are imperative for field seeding success (Lázaro-González *et al*., 2023). The subsequent growth rates and the physiology of lateral branching determine the effective competition with weeds for resources, especially light and space.

Field Seeding Technology

For the conventional LCCs (*P. phaseoloides*, *C. mucunoides*, *C. caeruleum* and *C. pubescens*), the seeds are sown directly in rows in between oil palms. While many planters also employ direct field seeding for the larger and more expensive *M. bracteata* seeds as a labour-saving approach, some still raise the seedlings in plug trays in the nursery, followed by transplanting them to the field.

In highly clayey areas or compacted sites, planters may prepare sandy drills for direct seeding of LCCs with some additional cost and labour usage (Kolawole *et al*., 2004). The sandy drills provide comparable advantages of water-logged avoidance, which otherwise will suffocate the newly sown seeds, as well as further seed scarification, as the sand has a relatively higher temperature under direct sunlight in the open site, and improved aeration for the germinating seeds. After successful seed germination, the radicles of LCC elongate into the soil beneath the sandy drills to source water and nutrients. Well-developed root systems ensure the survival of the seedlings and their ability to face temporary dryness following a short no-rain period.

The use of a wooden spike has been another innovative idea among the planters to ease the sowing of the large *M. bracteata* seeds under the hot sun in open fields. With an additional rubber stopper, a worker can even carry out hole-making of appropriate depth for gaining the best seed germination effects. Immediately after holing, the worker will deposit about three seeds into each hole and complete the seeding job conveniently by covering the hole with some soil using one of his feet. Without the need to bend down, such a seeding technique saves time and energy, and has gained favour in the direct field seeding of *M. bracteata*.

Seed Rate

An appropriate seed rate of LCC is a key factor in expediting ground cover and extending weeding cycles in oil palm plantations. *Pueraria phaseoloides* with a germination rate of about 70% can be sown at about 5 kg seeds/ha in single LCC species planting but some planters apply a higher seed rate of up to 9 kg/ha to have the ground almost fully covered by this LCC within six months (Ekeleme *et al*., 2004; Heuzé *et al*., 2016; Prasannakumari *et al*., 2014; Shelton & Stür, 1991; Tropical Forages, 2024). When mixed with *C. mucunoides*, *C. caeruleum* or *C. pubescens*, planters adopt varying ratios of *P. phaseoliodes* to other LCC at a total seed rate of 7-9 kg/ha, mostly depending on site attributes, waterlogging and microclimatic factors (Halim, 1997).

Mucuna bracteata is another single LCC for oil palm but a much lower seed rate of 150-250 g/ha, either as field seeding or transplanting of nursery-raised seedlings, because of its much higher price in comparison to other conventional LCC seeds (Prasannakumari *et al*., 2014). Thus, planters compromise the complete ground cover with *M. bracteata* within a year, while this LCC is more effective than the conventional LCCs to smother weeds and regulate atmospheric N fixation in years to come.

Seeding Time

With direct field sowing or transplanting of seedlings, LCC planting is usually planned with the onset of rainy seasons. Despite having drought tolerance attributes, sufficient and consistent water supply is critical for optimal seed germination and growth of the tender young plants during the early stage. For field seeding in periods of rain scarcity or under uncertain water availability, the incorporation of hydrogel in the drills has been a consideration pending the cost-effectiveness justifications within the aspects of ground shielding and N fixation rates by LCCs versus fertilisation and weed management expenses (Barros *et al*., 2017; Skrzypczak *et al*., 2021; Su *et al*., 2017). After about two months, most LCC seedlings develop a substantial amount of leaves to conserve moisture of some rooted points, and thus, they can generally face a temporary dryness effectively by shedding only some plant parts, while the living meristematic points will resume active growth with subsequent rain (Tsan *et al*., n.d.).

Enhancing Axillary Growth of Vines

Effective ground cover is dependent on both the growth rate and architectural form of the cover crop. LCC that demonstrates speedy vine elongation in combination with extensive lateral growth from the initial main vines is advantageous. By manipulating an optimal or cost-effective seed rate, the LCC then controls the weeds and conserves the soil in plantations quickly.

On the other hand, *M. bracteata* shows apical dominance by extending the main stem far from the initial growth point (Chiu & Bisad, 2006; Mohd Noor *et al*., 2021). In other words, the adventitious roots and lateral shoots do not form spontaneously from the nodes of this LCC despite touching the soil. To accelerate ground cover, planters clip the main stems to remove the latest 6-8 nodes, which enhances the branching and rooting from the nodes. Alternatively, growers pull around the long vines to break their apical dominance while the axillary growth from the nodes is initiated simultaneously. Likewise, lateral shoot development is promoted when the tender young apical shoots dry out and die following a certain no-rain period under unattended rain-fed field conditions.

Fertilisation

Mineral supplements positively support plant growth (Arnott *et al*., 2021). Although LCCs add N significantly through atmospheric N fixation, they respond well to simultaneous fertilisation. Planters often apply rock phosphate for LCCs since these cover crops that live symbiotically with rhizobia lower the rhizosphere pH, therefore enhancing the dissolution of rock phosphate. Otherwise, LCCs are provided with any available low-cost fertilisers to accelerate ground cover and to better support the sustainability of the main crops (Tsan *et al*., 2023). Fertilisation of LCCs will usually cease upon achieving 50% ground cover as the photosynthetic activity of the generated bulk is sufficient to bring on exponential growth of the LCC. Likewise, the partial ground cover by LCCs also improves soil moisture conservation, being synergistic in attaining a complete ground cover within the next few months.

Control of Overshading of Oil Palm by LCC Vines

Fast-growing LCCs, especially *P. phaseoloides* and *M. bracteata*, will have vines climbing onto the oil palms, resulting in significantly reduced light availability and impacting the growth of the crop. This is particularly critical for the immature oil palms with low fronds. Manual management of the LCC vines that get tangled in the fronds is not only time-consuming but is also ineffective, because this practice stimulates new shoot development from their nodes. Conversely, clearing the LCC vines around the palms with some suitable herbicides is easier and more effective in solving this problem. Chemical control of the LCC vines also lasts for a longer period. Metsulfuron-methyl as a low-toxicity herbicide alone or in a mixture with a low dosage of glyphosate isopropylamine was proven effective for the circular control of the LCCs without harming the oil palms (Goh *et al*., 2014, 2015).

More studies are yet to be carried out to get a glimpse into the future so that the LCC-oil palm synergistic associations are more ecologically impactful while reducing the carbon footprint in palm oil production. Depending on the local climatic condition and physicochemical properties of soil, planters need to justify the choice of LCCs, regulate the sowing of the different LCC species and their growth rhythms in reducing competition with the oil crop while enriching soil properties and providing other ecosystem advantages in the plantations (Kocira *et al*., 2020).

THE WAY FORWARD

As we emphasise Roundtable on Sustainable Palm Oil (RSPO) and Malaysian Sustainable Palm Oil (MSPO) certifications to meet the market needs and to promote eco-friendly crop production, this review is hoped to spur a greater interest in the cultivation of LCCs among planters who have yet to perceive the agronomic advantages of LCCs to be worth the cost (*Figure 5*). These planters should be made aware of the cost-benefit analysis that indicates the trade-offs between the initial cost of LCC planting and the potential benefits of improved soil properties, controlled erosion and savings following reduced fertiliser and herbicide uses in the long run.

As we move towards a technology-based concept in plantations, advancements in seed technology could be manipulated to improve LCC planting (*Figure 5*). Some novel conditioning or treatments could be researched as prospective techniques to improve seed handling, germination, field performances and resistance to pests (Brown *et al*., 2021; Rifna *et al*., 2019; Zhao *et al*., 2024). For a number of vegetable and cash crops, the applications of seed coating have gained momentum and are partly applied in field seeding to resolve some difficulties that arise from unpredictable and changing environments (Razak *et al*., 2023). In this context, the seeds are coated with some fine colloidal materials or slurry mineral products and binders through a fluidised bed and rotating drum (Jarrar *et al*., 2023; Javed *et al*., 2022). In exploring the knowledge that can improve the germination and growth of LCCs with direct field seeding techniques, coating the LCC seeds with ingredients of hydrogel could be studied to sustain the moist condition of the germinating seeds. The coating could also include additional lower-cost but higher-efficiency ingredients or any other new edge materials as seed enhancement technologies in facing the edaphic abiotic stresses or for releasing pesticides and nutrients slowly and steadily after field sowing. The evolving seed coating technologies could also be potentially favourable for extending the shelf-life of the bulk of LCC seeds where the coat is beneficial to protect the seeds from fluctuating ambient relative humidity and therefore, loss of viability and vigour during storage. However, the up-scaling of LCC seed coating requires refinement of the formulation depending on the targeted issues, and more importantly, should be well justified and cost viable.

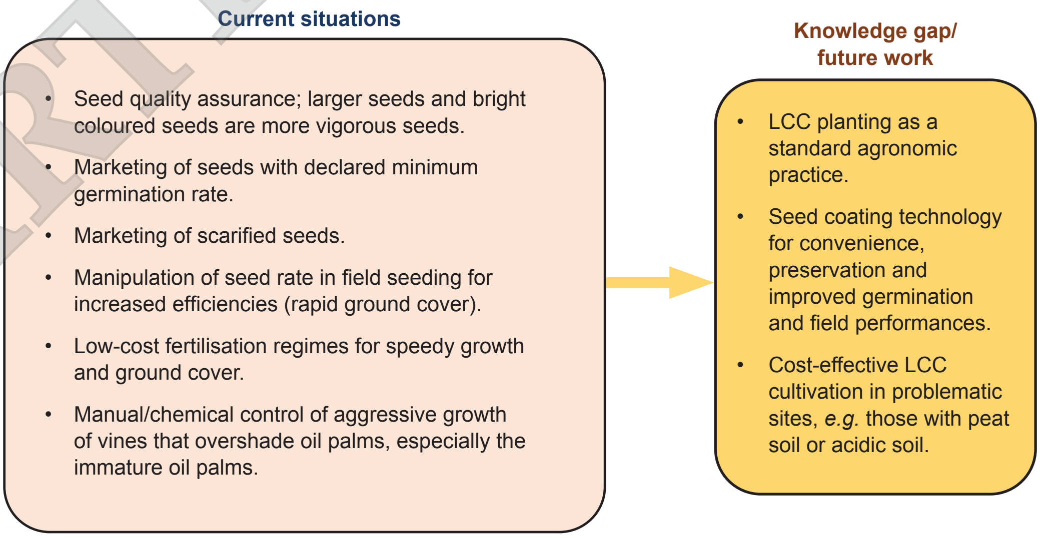

Figure 5. The technology of leguminous cover crop (LCC) cultivation in Malaysian oil palm plantations.

For problem sites like those of peat soil or acid sulfate soil, attention should be paid to selecting suitable LCC species or improved techniques to promote the survival and growth of these creeping plants. Based on the morphological, phenological and physiological characteristics of the different LCCs and innovative strategies in site-specific LCC cultivation, further research is needed to determine the potential positive impact of LCCs for ameliorating the quality of the less favourable oil palm sites. Low-cost soil pH improvement techniques are another research subject to be explored for enhancing the growth of both the LCCs and oil palms in these acidic areas.

This review also calls for other related research clusters and gaps to improve the appropriateness of LCC seeding *vs*. habitat or site circumstances in oil palm fields. The survival and performances of LCCs have economic implications in both the immature and mature stands. Thereafter, the many biotic and abiotic factors and their interactions are also common threats to sustaining the oil palm sector while LCC as ground cover could ameliorate stresses faced by these oil crops in the fields.

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