

IMPACT OF *Elaeidobius kamerunicus* (Faust) INTRODUCTION ON OIL PALM FRUIT FORMATION IN MALAYSIA AND FACTORS AFFECTING ITS POLLINATION EFFICIENCY: A REVIEW

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ABSTRACT

The oil palm pollinating weevil, *Elaeidobius kamerunicus*, has become the single most important insect pollinator of the commodity crop in Malaysia and Indonesia, 40 years after its introduction. However, in 2020, the average national oil extraction rate (OER) has decreased from 20.21% to 19.92%. The decline was attributed to the lower oil palm fruit bunch quality. This has raised concerns on the pollination efficiency of the pollinator. As such, the factors affecting the pollination efficiency of *E. kamerunicus* were thoroughly discussed in this review. Eight factors, which were categorised into intrinsic and extrinsic factors, were discussed in detail. Intrinsic factors discussed are the genetic make-up of *E. kamerunicus* and its population level. Meanwhile, factors such as planting materials, soil types, plant physiological condition, volatiles emission, diseases/predators threatening *E. kamerunicus* and climatic factors were discussed in the extrinsic factors. Methods for maintaining a healthy pollinator population were suggested, as well as an emphasis on future studies based on the shortlisted factors.

Keywords: *Elaeidobius kamerunicus*, *Elaeis guineensis*, pollination efficiency.

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INTRODUCTION

Malaysia is one of the prominent major exporters of palm oil, contributing to 34.30% of the total palm oil trade (Parveez *et al.*, 2021). In Malaysia, 5.87 million hectares of land are currently under oil palm cultivation (Parveez *et al.*, 2021). In 2020, the total Malaysian export revenue increased by 8.40% compared to RM64.84 billion collected in the previous year (Parveez *et al.*, 2021). In the 2020 overview, Malaysian Palm Oil Board (MPOB) stated that the worldwide COVID-19 pandemic had disrupted the production of crude palm oil (CPO). However, the tight supply of CPO led to a higher CPO price and more significant export revenue of palm oil products (Parveez *et al.*, 2021). It was also reported that in 2020, the oil extraction rate (OER) in the palm oil mills declined from 20.21% to 19.92%, mainly due to the reduced quality of fresh fruit bunches (FFB) supplied to the mills (Parveez *et al.*, 2021). The lower quality bunch was usually associated with inadequate pollination, which will also reduce the bunch yield and CPO production (Harun and Noor, 2002; Rao and Law, 1998).

In Malaysia's early phases of oil palm cultivation, the formation of oil palm fruit was unsatisfactory, especially in young palms (Syed, 1979). It was observed that poor fruit set formation was due to insufficient pollination, which largely depended on wind and inefficient locally-available insect pollinators (Hardon, 1973; Lewis, 1973; Pardede, 1990; Syed, 1979; Wood, 1968). In the event where pollination is insufficient, the domestication of insect pollinators has been previously done. For example, the introduction of the European honey bee (*Apis mellifera*) was instrumental in increasing the forage production in Hawaii, United States in 1857 (Messing, 1991; Valenzuela, 2018). Similarly, to increase the pollination of tomatoes in North America, Australasia, Asia, Africa, and South America, the introduction of bumblebee (*Bombus terrestris*) was conducted (Velthuis and van Doorn, 2006). Another notable example is the domestication of sting bees in tropical and sub-tropical regions (*Melipona* sp., *Trigona* sp.) to assist in the pollination of crops such as avocado, coconut, coffee, macadamia, and mango (Can-Alonzo *et al.*, 2005; Heard, 1999; Slaa *et al.*, 2006; Viana *et al.*, 2014).

To improve the oil palm fruit formation, Malaysia decided to import insect pollinators from Africa (Kang, 1999). The importation efforts led to the mass-field introduction of *Elaeidobius kamerunicus* on three sites in early 1980 (Kang, 1999; Kang and Zam, 1982; Syed *et al.*, 1982). The introduced pollinator has since thrived well in the oil palm plantations throughout Malaysia and positively influenced the palm oil

industry in the country (Donough and Law, 1988; Kang and Zam, 1982; Lubis and Dono, 2017; Syed *et al.*, 1982; Wahid and Kamarudin, 1997; Yee *et al.*, 1985).

Despite the positive impacts of *E. kamerunicus* introduction, there have been increasing reports of parthenocarpic fruits and poor fruit set formation (Kamarudin *et al.*, 2018). In the MPOB survey, poor fruit set formation was observed primarily in peat areas in Sarawak, Malaysia (Sulaiman *et al.*, 2018). The OER has also stagnated and has yet to achieve the favourable OER of 23% (Parveez *et al.*, 2021). In line with the industry's sustainable aspirations, the Malaysian government has mandated a cap on oil palm cultivation area at 6.5 million hectares (The Malaysian Reserve, 2019), which means that the improvements in yield must be made without clearing up additional areas. To address the issues related to poor fruit set formation, a Task Force Committee on Fruit Set and Pollinating Weevil comprising of experts from the MPOB, palm oil industry representatives, and related researchers from local universities was formed.

Given the massive economic importance of the palm oil industry and its reliance on efficient pollination services rendered by *E. kamerunicus*, investigating the factors influencing pollination efficiency and proper management of the pollinator population in the oil palm ecosystem should be imperative. In this article, we present a review that dates to the introduction of *E. kamerunicus* in Malaysia. This review also discusses the impacts of the introduction of *E. kamerunicus* on the Malaysian palm oil industry, the factors influencing its pollination efficiency, and ultimately, the management aspects of maintaining its population in the oil palm environment. We conclude by highlighting gaps in the current understanding of fruit set formation factors and identifying potential areas for further improvement.

The Pollinating Insects of Oil Palm

During the early stages of oil palm production in Malaysia, the lack of insects visiting oil palm flowering inflorescences led to the notion that the crop is anemophilous, or wind-pollinated (Hardon and Turner, 1967; Lepesme, 1947; Wood, 1968). Although many insects visited *Elaeis guineensis* inflorescences, these insects only visited specific sexes of the inflorescences. Derelominae, bees, and tabanids only visited the male inflorescences while female inflorescences were only visited by *Pyroderces* spp. (Lepesme, 1947; Syed, 1979). Hence, it was thought that these insects do not offer any pollination services to the oil palm (*i.e.*, no pollen was transferred from male inflorescence to female inflorescence). The onset of rains led to a massive reduction of pollen density in the air (Hardon

and Turner, 1967). Somehow, even during regular rainfall, when the pollen availability in the air was minimal, the natural pollination was sufficient and it was then suggested that the insects are playing a vital role in the pollination of the crop (Syed, 1979).

In Cameroon, Africa, Syed (1979) observed that the pollination was satisfactory, with the annual mean of fruit/bunch ratio of 64.8%. Pollination is considered satisfactory if the fruit weight ratio to total bunch weight exceeds 60.0% (Hardon, 1973). In contrast to what was observed in Malaysia, many insects visited both sexes of oil palm inflorescences during anthesis. It was noted that the most abundant species visiting the inflorescences of oil palm were *Elaeidobius* spp. and *Atheta* spp. Unlike Cameroon, less diverse insect species visited oil palm inflorescences in Malaysia (Syed, 1979). In Peninsular Malaysia, only *Thrips hawaiiensis* was observed inhabiting and moving around the anthesising inflorescences (Syed, 1979). *Thrips hawaiiensis* is reported to be a weak flyer and thus has less tendency to fly into open, windy areas, even when the area is closer to older palms (Lewis, 1973; Syed, 1979). Whereas, in Sabah, Malaysia, besides an unidentified midge, many momphid moths (*Pyroderces* spp.) were observed visiting the oil palm inflorescences (Syed, 1979). In Peninsular Malaysia, pollination on the tall palms was found to be sufficient. However, the same cannot be said for younger palms. In such areas, manual hand-assisted pollination has to be done to improve the fruit set formation.

Appiah (1999) observed several insect species (*Elaeidobius* spp. and *Prosoestus minor*) visiting the oil palm inflorescences in Ghana, where the fruit set formation was adequate and uniform throughout the year. Similarly, Mariau and Genty (1988) observed the activities of *Mystrops costaricensis* and *Elaeidobius subvittatus* on the American oil palm, *Elaeis oleifera*. *Elaeidobius subvittatus* was suggested to be introduced to the region from Africa (Mariau and Genty, 1988), before colonising entire Neotropical America (Appiah and Agyei Dwarko, 2013). However, although the presence of the pollinating insect species was observed, the fruit set formation in the area was still inadequate (Mariau and Genty, 1988).

It was clear that insects play an essential role in the pollination of oil palm. The lack of pollinating insects led to poor fruit set formation in Southeast Asia (Syed, 1979). Comparatively, the pollination in the African region is much more satisfactory than those in America and Southeast Asia, possibly due to the presence of various insect pollinators species in the region, which ensured adequate pollination (Appiah, 1999; Syed, 1979; 1981). To supplement the pollination activity by native insect pollinators

and to improve fruit set formation in Malaysia, the importation of insect pollinators from Africa was suggested (Kang, 1999).

Selection of Pollinator to be Introduced into Malaysia

Syed (1979) reported that in Cameroon, where natural pollination is deemed adequate, about a dozen insect species were observed pollinating the oil palm. Therefore, selection for the most suitable pollinator to be introduced in Malaysia had to be conducted. Furthermore, more insects are seen visiting male inflorescences compared to female inflorescences. The most abundant species found on male inflorescences were *E. kamerunicus*, followed by *E. subvittatus*, *E. plagiatus* and *Atheta* spp. (Syed, 1979). In terms of the number of pollen grains transported, males of *E. kamerunicus* and the females of *E. plagiatus* were reported to carry an average of 235 and 203 pollen grains, respectively, more significant than other species (Syed, 1979). This figure did not differ much from a recent study by Kouakou *et al.* (2014). They reported that the adult *E. kamerunicus* was able to carry 317 pollen grains. However, Dhileepan (1992) reported that adult *E. kamerunicus* can carry more pollen, ranging from 610 to 2620 grains. The pollen carrying capacity (PCC) was inversely proportional to the pollinator population per spikelet, which means the low number of adult *E. kamerunicus* visiting the inflorescences meant more pollen was available to be carried by an individual insect pollinator, which is the most probable scenario in India, where the sole insect pollinator of the oil palm is *E. kamerunicus* (Dhileepan, 1994), compared to the relatively higher insect pollinator complex in the African region (Kouakou *et al.* 2014; Syed, 1979). Moreover, the population of the insect pollinator on male inflorescences was comparatively lower in India (18.7 to 99.2 *E. kamerunicus* per spikelet) (Dhileepan, 1992) than in Cameroon (1473 *E. kamerunicus* per spikelet) (Syed, 1979).

The abundance of insects visiting the oil palm inflorescences in Africa was observed in both dry and wet seasons, which indicates that changing weather conditions did not affect the population density of these pollinators (Syed, 1979). Due to their better pollen transport capacity and ability to flourish in wet and dry seasons, *Elaeidobius* spp. were chosen as pollinators (Syed, 1980).

Elaeidobius spp. is a curculionid within a small sub-family of Derelominae. *Elaeidobius kamerunicus*, native to tropical Africa, is now distributed into all tropical regions where *E. guineensis* are planted (Haran *et al.*, 2020). Lepesme (1947) reported that the geographical distribution and hosts of the various genera of Derelominae are remarkably restricted (*e.g.*, *Derelomus* in the Mediterranean area is found

on *Chamaerops*; *Meredolus* is found on *Cocos* in the Pacific; *Prosoestus* and *Elaeidobius* on *Elaeis* in West Africa). This information indicates this sub-family specialised nature, a handy feature in selecting insects to be introduced into Malaysia.

In Cameroon, six species of *Elaeidobius* spp. were found visiting male and female flowers of the oil palm inflorescence: *E. kamerunicus*, *E. plagiatus*, *E. singularis*, *E. subvittatus*, *E. bilineatus* and *E. spatulifer* (Syed, 1980). Other Derelominae (i.e., *Prosoestus sculptilis* and *P. minor*) were usually found only on female flowers. Out of the six *Elaeidobius* spp., three species were observed to be the most abundant, viz., *E. kamerunicus*, *E. plagiatus*, and *E. subvittatus* (Syed, 1980).

The abundance of *Elaeidobius* spp. is influenced by the anthesis stage of the inflorescence. The maximum number of insects were found during the third day of anthesis when most florets have opened. These numbers will drop on the fourth and fifth anthesis (Syed, 1979; 1980). Auffray *et al.* (2017) observed that the peak activity of *E. kamerunicus* was synchronised with the anthesis stage of both male and female inflorescences, which helps to maintain the mutualistic insect-plant relationship. *Elaeidobius kamerunicus* (160 individuals per spikelet) was more abundant than the other species (*E. subvittatus* = 22 adults per spikelet; *E. plagiatus* = 21 adults per spikelet). During the rainy season, high larval mortality in both *E. plagiatus* and *E. subvittatus* result in a significant reduction of the adult population in the field. However, *E. kamerunicus* was less affected (Syed, 1980). A summary of this explanation, as suggested by Syed (1980), is listed in Table 1.

Syed (1980) also compared the pollinator population on different palm age profiles. In general, younger fields contain a high inflorescence

sex ratio (higher number of oil palm female inflorescences). The ratio will naturally diminish over time, which means that the density of male inflorescences will naturally increase as the planting age (Corley, 1976a; Sparnaaij, 1960). It was observed that *E. plagiatus* and *E. singularis* were more numerous in the field with a high density of male inflorescences and *vice versa*. Meanwhile, the number of *E. kamerunicus* was either similar or proportionately low. This suggested that *E. plagiatus* and *E. singularis* have a weaker searching ability than *E. kamerunicus* (Syed, 1980). In contrast, the abundance of *E. subvittatus* in younger fields and higher ground elevations indicated this species' superior searching ability (Syed, 1980). Further trials indicated that *E. subvittatus* has the strongest searching ability, followed by *E. kamerunicus* and *E. plagiatus*. However, *E. subvittatus* was found to be less selective in choosing their host plants, having been observed to breed well on *E. oleifera* (Syed, 1979; 1980). Other species, on the other hand, appeared to be attracted solely to *E. guineensis* (Syed, 1980).

Based on the series of trials and observations, it was found that the most suitable species for introduction to Malaysia was *E. kamerunicus*. This was because it was the most abundant species under the coastal climatic conditions (Kang and Zam, 1982; Syed, 1980). In addition, it had superior pollen transferring capability, was able to adapt to both dry and wet conditions, possessed the good searching ability, and most importantly, extremely host-specific (Auffray *et al.*, 2017; Kang and Zam, 1982; Syed, 1980). The introduction of *E. kamerunicus* in Malaysia was executed by packing the larvae and pupae in July 1980, followed by field release in February 1981 at the Pamol Plantations, Kluang, Johor, Malaysia (Syed, 1982; Kang, 1999).

TABLE 1. EFFECTS OF RAINY SEASON ON THREE DIFFERENT MAIN POLLINATING INSECTS ON MALE INFLORESCENCES OF *Elaeis guineensis*

Species	Risky behavioural pattern during the wet season	Effects of rains
<i>Elaeidobius kamerunicus</i>	Location of egg oviposition: The outer side of the anther tube	Comparatively, the drier outer side of the anther tube is less favourable than the inner side of the anther tube for fungi growth. This minimised the fungi infection on first instar larvae and contamination of larvae food source.
<i>E. plagiatus</i>	Location of egg oviposition: Inside of the anther tube	Indirect - Wet circumstances favour the development of fungus, which destroy male inflorescences. Following that, the development of first instar larvae was disturbed.
<i>E. subvittatus</i>	Location of egg oviposition: Just below the anther tube	Direct - The egg is superficially positioned, making it very vulnerable to the run-off effects of heavy rains. Emerged larvae were likewise eating on the shallow portion of the anther and were similarly exposed to danger.

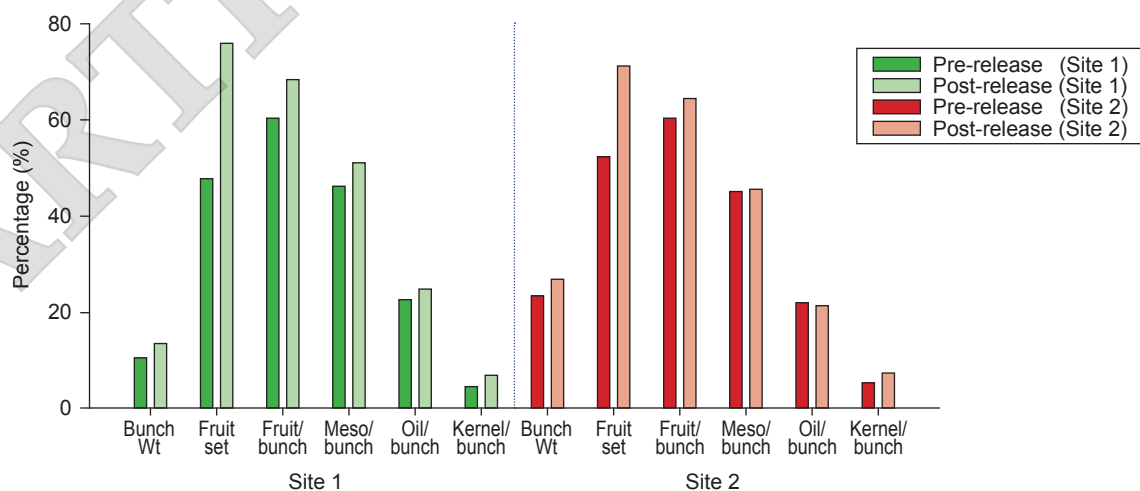
Source: Syed (1980).

Impacts of *E. kamerunicus* Introduction in Oil Palm Plantation

Effects of the introduction of *E. kamerunicus* on the oil palm yield in Malaysia. The impact of the introduction of *E. kamerunicus* to oil palm plantations in Malaysia was immense. The introduction increased the level of pollination (Basri *et al.*, 1983; Choong *et al.*, 2004; Syed *et al.*, 1982). Syed *et al.* (1982) reported that after *E. kamerunicus* introduction, the oil palm yield-related components showed a marked increase. According to Harun and Noor (2002), pollination by the weevils increased fruit set compared to assisted hand pollination by approximately 20%. The enhanced fruit set resulted in an increased bunch weight from a higher fruit-to-bunch ratio (Harun and Noor, 2002). *Figure 1* shows the increments of yield-related components after the introduction in two sites (Site 1 and Site 2) in Johor.

Indirectly, with an increased level of entomophilous pollination with *E. kamerunicus*, the practice of manual pollination was no longer necessary (Kevan *et al.*, 1986; Wahid and Kamarudin, 1997). The manual pollination practice was expensive, given the massive number of palms and areas covered in plantation settings (Alvarado *et al.*, 2013; Choong *et al.*, 2004). Thus, immense savings were made by doing away with the practice. Hussein *et al.* (1991) reported in their study that the introduction of the pollinating weevil allowed the industry to save approximately USD60 million annually. Due to this, the weevil was dubbed as the 'multi-million-dollar weevil' to recognise its massive contribution to the Malaysian palm oil industry (Greathead, 1983; Krantz and Poinar, 2004).

Effects of the introduction to local oil palm pollinating insects in Malaysia. The specific nature of the feeding pattern and habitat preference of *E. kamerunicus* posed minimal risks to other plants in Malaysia (Kang and Zam, 1982; Syed, 1980). However, its introduction had potential effects on the locally available oil palm pollinators (Kang and Zam, 1982). The study on the effects of *E. kamerunicus* introduction on the local pollinators was reported initially by Syed *et al.* (1982) and later by Wahid and Kamarudin (1997) and Anggraeni *et al.* (2013). Interestingly, there was no competition for food sources between *E. kamerunicus* and *T. hawaiiensis*. The latter was observed to feed on pollen grains, while *E. kamerunicus* feeds on anther tubes (Wahid and Kamarudin, 1997). However, weevils occupied the anthesising part of the male inflorescences, which created a disadvantage for the thrips (Syed *et al.*, 1982). As a result, the number of thrips on the anthesising male inflorescences was declining. Nevertheless, Wahid and Kamarudin (1997) reported that *E. kamerunicus*, *T. hawaiiensis*, and *Pyroderces* could co-exist. This was attributed to the different habitat requirements for pupation, *i.e.*, thrips pupates in the soil while *E. kamerunicus* and *Pyroderces* pupate in spent male inflorescences (Jagoe, 1934; Syed, 1981). In addition, thrips thrive better in dry conditions than weevils (Wahid and Kamarudin, 1997). Additionally, all three species are not active simultaneously, with weevils activity peaking around 1000-1100 hr, while thrips and *Pyroderces* are about 0800-0900 and 1400-1500 hr (Anggraeni *et al.*, 2013) and past-sunset (Wahid and Kamarudin, 1997), respectively, thus allowing them to co-exist well.



Source: Syed (1982).

Figure 1. Impacts of the *Elaeidobius kamerunicus* introduction on oil palm bunch composition in two sites in Malaysia.

Factors Influencing the Pollination Efficiency of *E. kamerunicus*

Based on a recent survey conducted by MPOB, the incidence of poor fruit set formation, and stagnating OER was reported on a substantial number of estates, covering an estimated area of more than 88 000 ha, mainly in peat soil areas (Kamarudin *et al.*, 2018; Sulaiman *et al.*, 2018). In addition to OER, low kernel extraction rate (KER) was also used to indicate the poor fruit set formation (Choong *et al.*, 2004). There were inquiries about the need to import new generations or species of pollinators. Intriguingly, poor fruit set formation has also been recorded in Indonesia (Prasetyo and Susanto, 2013; Prasetyo *et al.*, 2014). This has prompted research into the factors that may influence *E. kamerunicus* pollination efficiency. After deliberate discussion in the Task Force Committee meeting, predominant factors were shortlisted and discussed in detail in this review. The factors can be divided into two main categories: intrinsic and extrinsic factors (Figure 2), as suggested by Costa *et al.* (2018).

(a) Intrinsic factors

Genetic make-up of *E. kamerunicus*. The initial generation of *E. kamerunicus* introduced to Malaysia in 1981 started from 600 weevil pupae, after having discarded dead, unhealthy, and moribund pupae

of the weevil (Syed, 1982). Since then, no further introductions have been made. This led to the belief that pollinating weevils in Malaysia may be suffering from inbreeding depression due to their limited genetic basis, which has negatively influenced pollination efficiency. The detrimental consequences of insect inbreeding have been extensively documented. For example, Fox *et al.* (2007) reported that the inbred larvae of the seed beetle, *Callosobruchus maculatus* (Coleoptera), took a long time to develop to emergence compared to a recent field-collected population. In addition, the larval survival rate is also reduced in the inbred populations. Vitikainen and Sundström (2010) suggested that the genetic stress induced by inbreeding has affected *Formica exsecta* (Hymenoptera) immune defense. Meanwhile, inbreeding depression impacted the lifespan, fecundity, and sex ratio of the parasitoid *Uscana semifumipennis* (Hymenoptera) (Henter, 2003). Similarly, inbreeding in the seed bug, *Oncopeltus fascia* (Hemiptera), resulted in fewer eggs production and a higher progeny mortality rate (Turner, 1960).

Morphological evolution of the domesticated weevil against samples from its region of origin was also used as possible indicators. Muhammad Nasir *et al.* (2020) found a distinct separation in the morphometric characters between the samples in Malaysia and Cameroon. Similarly, Latip *et al.* (2019) concluded that separation existed among the

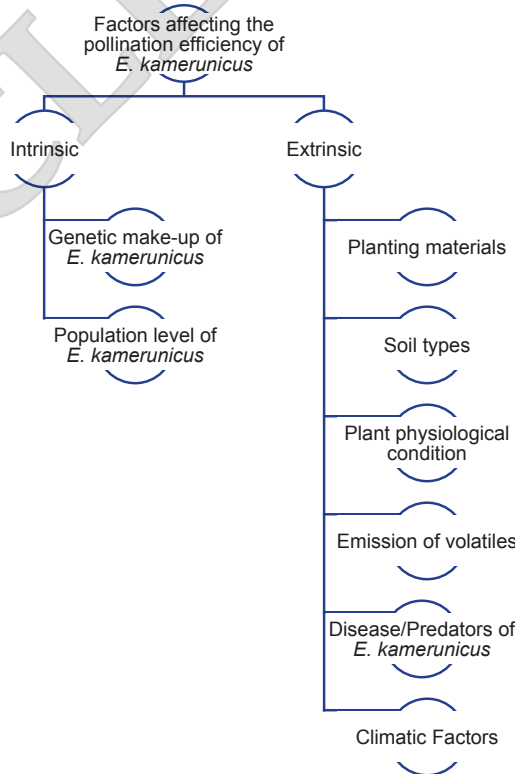


Figure 2. Factors affecting the pollination efficiency of *Elaeidobius kamerunicus* discussed in the MPOB-Industry Task Force Committee Meeting on Fruit Set and Pollinating Weevil.

E. kamerunicus samples from Malaysia, Indonesia, and Liberia. However, they concluded that genetic comparison has to be conducted to validate the results further. Li *et al.* (2019) also suggested that future research should prioritise the study on the effects of homozygosity and inbreeding depression on the introduced oil palm pollinators. Bakara *et al.* (2019) reported that no evidence of inbreeding was found in *E. kamerunicus* populations in Indonesia. In addition, the preliminary data on the genetic study presented to the Task Force Committee suggested similar findings for the adult *E. kamerunicus* sampled from Malaysian, Indonesian, and Papua New Guinea (PNG) oil palm estates. Similar findings were expected as Indonesia sourced the weevils through Malaysia (Hutauruk *et al.*, 1982; Prasetyo and Susanto, 2016). Deleterious recessive alleles that cause inbreeding depression can be 'purged' in both controlled and natural conditions, for example, in *Drosophila melanogaster* (Perez-Pereira *et al.*, 2021; Swindell and Bouzat, 2006) and *Harmonia axyridis* (Facon *et al.*, 2011). This possibly explains the lack of inbreeding depression in the introduced *E. kamerunicus* in Southeast Asia (Bakara *et al.*, 2019).

In contrast, Haran *et al.* (2020) suggested the introduced *E. kamerunicus* populations in Asia and the South America region may experience a bottleneck. Genetically, the *E. kamerunicus* populations in Asia (*i.e.*, Malaysia, Indonesia, Thailand and Myanmar) and South America (*i.e.*, Guatemala, Brazil, Colombia, and Ecuador) belong to both Western and Central Africa. They also found a low haplotype number across all Asian populations of *E. kamerunicus*, which suggests that the introductions were made from a limited number of individuals, contributing to a limited genetic base among these populations. Indeed, for the Malaysian population, Syed *et al.* (1982) reported that out of 1200 pupae, only 600 individuals survived upon arrival in Kuala Lumpur, Malaysia from Cameroon. However, Haran *et al.* (2020) agreed that more research is needed to determine how genetic bottlenecks affect the pollination rate. Therefore, studies on the dispersal behaviour and fitness of the current generation of *E. kamerunicus* in Malaysia are needed to enable a better understanding of the genetic patterns observed.

The population of *E. kamerunicus*. The population level of the pollinating weevil is a crucial factor in ensuring a satisfactory pollination level (Zulkefli *et al.*, 2020). The introduction of weevils into Malaysia has positively impacted the oil palm fruit bunch formation (Syed *et al.*, 1982). Since then, efforts to monitor its population in the field have been conducted by several researchers *e.g.*, Cik Mohd Rizuan *et al.* (2013); Daud and Idris (2016); Mohamad *et al.* (2021b); Wahid *et al.* (1987)]. Various minimum weevil requirements for a satisfactory

fruit set formation were suggested. Donough *et al.* (1996) recommended that 20 000 weevils ha⁻¹ are required for a fruit set of 55%. Meanwhile, Syed and Salleh (1987) reported that to obtain at least 70% pollination, approximately 3000 weevils per female inflorescence are needed. Meanwhile, Mohamad *et al.* (2021b) suggested that a population of 14 000 individuals ha⁻¹ was sufficient to obtain a good fruit set percentage of 65%.

During the first few months after the introduction of *E. kamerunicus*, Syed *et al.* (1982) reported that the introduced population increased rather rapidly. Due to palm height, the density of male inflorescence in the area, wind direction, and human intervention, the dispersal rate on older palms was faster than on the younger ones. During the initial phase of the introduction, the density of *E. kamerunicus* usually remained above 40 individuals per spikelet, reaching as high as more than 200 individuals per spikelet (Syed *et al.*, 1982). Several years after, the weevil population in Malaysia has stabilised to between 26 to 29 weevils per spikelet in Peninsular Malaysia and 32 individuals per spikelet in East Malaysia (Wahid *et al.*, 1987). Subsequent efforts were regularly conducted in monitoring the pollinating weevil population. Daud and Idris (2016) found that in an estate in West Malaysia, the weevil population ranged from about 14 to 54 individuals per spikelet. Whereas, in Sabah, the mean weevil population was 20 individuals per spikelet (Cik Mohd Rizuan *et al.*, 2013). Meanwhile, a smaller population was observed in peat soil regions of Sarawak, where the mean population size of the pollinating weevils was between 16 and 17 individuals per spikelet (Sulaiman *et al.*, 2018), a decline compared to the initial studies. However, it should be emphasised that the findings published by Wahid *et al.* (1987) were based on a single estate in Sarawak, and therefore do not necessarily reflect the whole state. Additionally, Mohamad *et al.* (2021a) found that in Sarawak, the average weevil population per spikelet in oil palm estates is located in mineral soil (26 weevils/spikelet) is greater than those in peat soil areas (15-21 weevils/spikelet).

One of the reasons *E. kamerunicus* was selected as the suitable candidate for the importation is its capability to withstand wet seasons, a natural and frequent condition in the tropics (Syed *et al.*, 1982). This was substantiated by findings by Daud and Idris (2016); Dhileepan (1994); Latip *et al.* (2018); Wahid *et al.* (1987), that rainfall did not have harmful effects on the weevil population. However, the event of drought (rainfall <100 mm month⁻¹) and excessive rainfall (> 370 mm month⁻¹) may adversely affect the weevil population level (Wahid *et al.*, 1987). However, it was pointed out that the resulting fruit set percentage is in an acceptable range even with the fluctuating

pollinator populations (Mohamad *et al.*, 2021b). These findings indicate that other causal factors could influence fruit set formation in addition to the presence of the pollinating weevil.

(b) Extrinsic factors

Planting materials. The crop's limited genetic base, which was derived mainly from direct descendants of seedlings brought to Indonesia in 1848, previously hampered oil palm productivity in Malaysia and exposed the crop to the threats of pests and diseases and productivity stagnancy (Rajanaidu *et al.*, 2000). To overcome this problem, MPOB initiated efforts to diversify the genetic profile of the crop via germplasm collection in the early 1970s (Rajanaidu *et al.*, 2013). This has enabled MPOB researchers to leverage the diversity of the germplasm in its extensive breeding programme for crop improvements. Disease resistance *e.g.*, Hanin *et al.* (2020); Maluin *et al.*, 2020, higher nutritional values, and industry-driven desirable traits (*e.g.*, short trunk height, short frond length, dwarfness, long-stalk, short rachis length) were given priority in the breeding programme (Idris *et al.*, 2004; Kushairi *et al.*, 2004; Noh *et al.*, 2005; Rajanaidu *et al.*, 2000; Teh *et al.*, 2020; Zulkifli *et al.*, 2017). Propagation of high-yielding materials through tissue culture has increased the yield by 25% (Rohani *et al.*, 2000). The most highly productive planting materials selected have a high sex ratio (Rohani *et al.*, 2000). A high inflorescence sex ratio tends to reduce the availability of male inflorescences in the field, limiting the food source and the breeding sites of *E. kamerunicus*, subsequently affecting its population (Bulgarelli *et al.*, 2002). Furthermore, pollen availability was also affected (Barcelos *et al.*, 2015). Some clonal palms, *e.g.*, the Federal Land Development Authority (FELDA) Clonal Palm (Latip *et al.*, 2018) and DxP Simalungun (Wahyuni *et al.*, 2019), were observed to have a higher number of spikelets, which meant more excellent food source and breeding sites available for the weevils. A higher number of spikelets contributed to a significantly greater *E. kamerunicus* population compared to standard planting materials (Latip *et al.*, 2018; Wahyuni *et al.*, 2019). Some planting materials, *e.g.*, DxP Simalungun (Indonesia), produced more pollen grains, due to the 25%-35% increase in the number of spikelets (Wahyuni *et al.*, 2019).

Soil types. The level of the productivity of a crop is heavily influenced by soil characteristics (Woittiez *et al.*, 2017). In Malaysia, due to the scarcity of suitable land for oil palm cultivation, the crop is planted in peat soils. The development of the peat soils was not ideal due to the issue of carbon emissions and climate changes *e.g.*, Murdiyarso *et al.* (2019); Yule (2010). However, many mitigation strategies for reducing carbon dioxide (CO₂) emissions in the oil

palm ecosystem have been proposed, including intercropping systems (Kusumawati *et al.*, 2021; Li-li *et al.*, 2015), soil fauna improvement, and appropriate farming practices (Paterson and Lima, 2018). Woittiez *et al.* (2017) suggested that biochemically constrained soils, such as peat soils, were identified as oil palm yield-limiting factors. Different characteristics of peat (*e.g.*, peat composition stage) substantially affected oil palm yield (Veloo *et al.*, 2015). Sulaiman *et al.* (2018) also noted that fruit set formation is better in mineral soil regions. Due to the frequent incidence of palm leaning, waterlogging and excessive drying, the crop yields on the peat soil are generally lower than those in mineral soil (Paramanathan, 2013). In addition, Veloo *et al.* (2015) suggested that the oil palm rooting was the main cause of the difference in the oil palm yield. The area with sufficiently decomposed peat (*i.e.*, sapric soils) has a better rooting and growth medium than undecomposed peat soil. Still, its level of high porosity means that it does not have good nutrient retention properties. The problem of nutrient leaching in this type of soil is especially severe in the event of heavy precipitation (Veloo *et al.*, 2015). The peat soil itself, mainly classified as Tropofibrists and Tropohemists in the United States Department of Agriculture (USDA) soil order of Histosols, has low nutrient content (except for nitrogen) and poor nutrient retention capacity, especially for potassium (Mutert *et al.*, 1999). Besides, the peat soil, with its large water holding capacity, posed a risk of water being stagnant during monsoon, and the reduced aeration can negatively affect the roots' formation and functionality. The reduced nutrient supply in the peat soil is usually manifested through shorter frond length (Mutert *et al.*, 1999), reduced vegetative growth, and smaller fruit bunch (Ng and Tan, 1974; Ng *et al.*, 1990; Turner and Bull, 1967). However, obtaining a high yield comparable to mineral soil is possible with proper planning and management strategies. For example, increasing the soil bulk density will bring subsequent positive impacts on soil capillarity, improved anchorage, and an increase in the supply of nutrients while minimising the risks of subterranean termite infestation (Mutert *et al.*, 1999). Furthermore, Zuraidah (2019) reported that the increase in soil bulk density and reduction in total porosity leads to an increase in oil palm yield. It was evident that the soil types on which the crop is cultivated heavily influence the nutrient availability of the crop, potentially altering the physiological development of the palm. This includes the inflorescence development and the volatiles emission, which in turn, affects the population and the behaviour of the pollinating weevil. Zulkefli *et al.* (2020) suggested that further understanding of the relationship between the soil types and their effects on the weevils' behaviour is required.

Plant physiological condition and morphological stress. The availability of male inflorescences affects the food sources and breeding sites for weevil (Eardley *et al.*, 2006; Syed *et al.*, 1982). The overall field density of the male inflorescences is influenced by various factors, among them are the soil types and the plant stress manifested due to water availability (Bulgarelli *et al.*, 2002; Corley, 1976a; Corley and Tinker, 2003). Oil palm has separate male and female flowers on the same plant, embodied in distinct male and female inflorescences (Corley and Tinker, 2003). The sex differentiation of the oil palm inflorescences, which usually occurs 22-24 months before harvesting, is influenced by moisture stress (Corley, 1976b). Prolonged drought will result in the increase of potential evapotranspiration (PET) in mature palms to around 10 mm daily, as opposed to normal PET of 5-5.0 mm daily (Foong, 1999). Whereas, during the wet period, the rate could be as low as 3.0 mm to 3.5 mm daily (Azlan *et al.*, 2016). In the period of prolonged drought and water deficit, it was observed that the palms tend to produce more male inflorescences (Adam *et al.*, 2011). However, this leads to reduced FFB production and lower yield. Zulkifli *et al.* (2017) highlighted intensive efforts in designing high-yielding palms. These planting materials have more female inflorescences but fewer male ones (Prasetyo *et al.*, 2012; Purba *et al.*, 2009). Normally, combinations of clonal palm and normal palm planting are recommended (Kushairi *et al.*, 2010). In the event of low availability of male inflorescences, Durand-Gasselin *et al.* (1999) suggested that the over-pruning of palm fronds can increase the production of male inflorescences. Increased male inflorescence production has also been reported when high-density planting is implemented *e.g.*, 148-86 palms ha⁻¹ (Breure *et al.*, 1990); 180 and 205 palms ha⁻¹ (Bonneau *et al.*, 2014). The situation results in decreased frond production, photosynthesis, female inflorescences, and fruit bunches (Bonneau *et al.*, 2014; Breure *et al.*, 1990). The balance between maintaining a healthy balance between the productions of both sexes of inflorescences is crucial as both are needed to maintain a healthy population of pollinating weevil and obtain satisfactory yield production.

Emission of volatiles. *Elaeidobius kamerunicus* relies on olfactory senses to guide it to oil palm inflorescences. Inflorescences of oil palm emit volatile organic compounds (VOCs), mostly estragole (4-allyl anisole) to attract *E. kamerunicus* (Hussein *et al.*, 1991; Lajis *et al.*, 1985; Muhamad Fahmi *et al.*, 2016). *E. kamerunicus* is primarily attracted to estragole emitted by *E. guineensis* due to the specific arrangement of the methoxy and allyl groups on the aromatic ring (Lajis *et al.*, 1985). Male inflorescences produce estragole and 1-dodecyne, for which *E. kamerunicus* has a high affinity, while female

inflorescences emit a variety of volatiles, primarily squalene and farnesol (Anggraeni *et al.*, 2013). This explains the larger number of *E. kamerunicus* found in male inflorescences (Anggraeni *et al.*, 2013; Lajis *et al.*, 1985; Syed, 1979). The level of estragole emission in oil palm was different depending on the soil types and planting materials (Idris *et al.*, 2018; Muhamad Fahmi *et al.*, 2016). In addition to the factors mentioned above, various environmental variables such as temperature, light intensity, and pathogen attacks significantly impacted the VOCs released from plants (Holopainen and Gershenzon, 2010). For example, an increase between 5°C and 10°C will cause the release of higher amount of phenethyl acetate in *Trifolium repens* (Jakobsen and Olsen, 1994). In addition to temperature, an increase in light intensity was also found to be inducing the release of a greater amount of VOCs in *Pinus elliotii* (Tingey *et al.*, 1980). In other plants, elevated level of VOCs release indicates the presence of pathogen attacks, as observed in legume *Medicago truncatula* (Leitner *et al.*, 2008), tobacco plants, *Nicotiana tabacum* (Huang *et al.*, 2003) and lima bean, *Phaseolus lunatus* (Yi *et al.*, 2009). Herbivory was also proven to induce an increased level of VOCs emission as a plant defensive response (Pare and Tumlinson, 1997; Turlings and Ton, 2006; Turlings and Tumlinson, 1992). In the event of herbivore injured *Zea mays*, an elevated level of terpenoid linalool emission was detected several hours after the damage was inflicted (Ruther and Furstenau, 2005; Turlings and Tumlinson, 1992). Similar observations were also reported in tomato, *Lycopersicon esculentum* (Frag and Pare, 2002), cotton plants, and *Gossypium hirsutum* (Pare and Tumlinson, 1997). Changes in the VOCs emission may alter the plant-insect relationship. In oil palm, Idris *et al.* (2018) suggested that the release of excessive estragole concentrations of 150 ppm and 200 ppm may result in repellent effects on *E. kamerunicus*. Other instances of the changes in the dynamics of plant-insect relationship due to the modification in plant VOCs emission were observed in cabbage, where the changes in the VOCs released by the plants affected the plant-host finding ability of *Plutella xylostella* (Li *et al.*, 2016). Similarly, the foraging activity of the herbivore *Rhopalosiphum maidis* was affected in the event of altered VOCs emission in barley (*Hordeum vulgare*) due to elevated atmospheric CO₂ concentration (Chen *et al.*, 2019). It was evident that multiple environmental factors can influence the pattern of plant volatiles emission, and modification in the composition and VOC emission level influenced the plant-insect relationship. It is essential to study the factors affecting VOCs emission in oil palm, and the extent of the elevated levels of estragole emissions effects on the density and behaviour of *E. kamerunicus* in the field and the oil palm fruit set formation.

Diseases or Predators of *E. kamerunicus*

Maintaining a sufficient population of *E. kamerunicus* in the field is important to ensure optimal fruit bunch formations. However, the presence of diseases, parasites, and natural enemies of the pollinating weevil may affect their general well-being, jeopardise their pollination efficiency, and threaten their survival if left unchecked. The following section of this review will discuss the types of diseases and predators of *E. kamerunicus* and the extent of their damage to the pollinating weevil.

Effects of parasitic nematode activities on *E. kamerunicus*. Parasitic nematode *Elaeolenchus parthenonema* was found living inside *E. kamerunicus* body (Poinar *et al.*, 2002). It was further revealed that although the nematodes could be present in both genders, the effects can only be seen on heavily infested female weevils, such as reduced egg production, causing them to be sterile, and reducing their size by reducing the fat reserves. The association with this nematode species probably may have a bearing on the weevil's pollination efficiency.

Microbes found on elytra/ parasitising *E. kamerunicus*. Hussein *et al.* (1991) reported that the bacteria *Serratia marcescens* was isolated from the gut of larvae and pupae from *E. kamerunicus* samples from sites in Peninsular Malaysia. The reported infection rates ranged from 11%-17% (larvae) to 9%-23% (pupae). *Serratia marcescens* is a pathogen of many insects (Aggarwal *et al.*, 2015; Flyg and Xanthopoulos, 1983; Kaaya and Darji, 1989; Steinhaus, 1959; Wei *et al.*, 2017) and is found to cause mortality in insects, such as *Spodoptera exigua* (Konecka *et al.*, 2019) and mosquitoes (Bahia *et al.*, 2014). However, the article by Hussein *et al.*, (1991) only reported on the presence of the pathogen on *E. kamerunicus* and did not further elaborate on its effects on the pollinating weevil. It will be interesting to assess the current rate of bacterial presence and its effects on *E. kamerunicus*.

Predator effects on *E. kamerunicus*. The high mortality rate of the immature weevils (*i.e.*, egg, larval, and pupal individuals) due to rat predation was reported previously (Chiu *et al.*, 1985). This was mainly observed at post-anthesis male inflorescences, where the immature weevils are abundant (Muhammad Luqman *et al.*, 2017; Syed, 1979). Rats start predating the weevils as early as the second day after anthesis (Hussein, 1984). The mortality rate was 82% and 85% on eight-years-old palms and 11-years-old palms, respectively. It was also observed that the damage was more severe in shorter palms, presumably due to easier access of

the rats to the crown region of the palm. However, during the study, even with the high rate of rat predation, the healthy weevil populations were sustained, between 54 000-95 000 individuals per hectare (Chiu *et al.*, 1985). Kamarudin *et al.* (2018) reported that in peat and mineral soils in Sarawak, Malaysia, the maximum weevil population is less than 50 000 individual ha⁻¹. So, a high rat population may affect the weevil populations in such areas, and proper rat population management procedures should be conducted. In Peninsular Malaysia, the usage of the barn owl (*Tyto alba*) as a biological control agent is common (Wood and Chung, 2003). According to Muhammad Syafiq *et al.* (2016), most of the owl species recorded in Peninsular Malaysia are associated with the oil palm ecosystem. However, the report of comparable practices in other areas of Malaysia was relatively sparse.

Elaeidobius kamerunicus is also preyed upon by reduviid bugs, *Cosmolestes picticeps*, and *Sycanus dichotomus* (Muhammad Luqman *et al.*, 2017). Both are prevalent in the oil palm environment and are often used as biological control agents to reduce bagworm populations (*e.g.*, *Metisa plana* and *Pteroma pendula*) (Azlina and Tey, 2011; Jamian and Nur Azura, 2018; Jamian *et al.*, 2017; Siti Nurulhidayah *et al.*, 2020). They were seen preying on mature *E. kamerunicus* on the surface of the male inflorescences. Muhammad Luqman *et al.* (2017) hypothesised that the predation rate on *E. kamerunicus* by both reduviids increased when the level of bagworm populations in the field is low.

Climatic Factors

Crops rely on soil and climate to thrive. While fertilisers can be used to change the chemical composition of soils, other factors such as soil physical features and climate temperature regimes are impossible to be altered in commercial settings. Oil palm is a generally tough crop and able to adapt to suboptimum climatic conditions (Gunawan *et al.*, 2020). There are instances in which minimal damages were inflicted on the crops even after an extended dry season (Corley and Tinker, 2003). However, plant-environment interactions are predicted to be impacted by climate change [Intergovernmental Panel on Climate Change (IPCC), 2014]. The expected increase in greenhouse gas (GHG) emissions will elevate the atmospheric CO₂. The influence of elevated atmospheric CO₂ on plant physiology is becoming increasingly well-documented [*e.g.*, Kumar *et al.* (2019); Zinta *et al.* (2018)]. In general, the elevated atmospheric CO₂ instigates an increase in the photosynthetic rates, which enables faster crop development (Li *et al.*, 2017). Interestingly, the impact of the elevated CO₂ on the development of *E. kamerunicus* was observed to be minimal (Amanina *et al.*, 2016). While the

findings from the cited experiment revealed that doubling the concentration of ambient CO₂ to 800 ppm had no significant effect on the emergence of *E. kamerunicus*, long-term effects on its biology and its adaptability to the elevated ambient CO₂ is yet to be fully understood.

Climate warming and changing precipitation patterns are the other aspects of climate change, which may influence the plant-insect relationship. It has been reported that elevated temperature may affect pollination, either on the physiology of the plant itself *e.g.*, sterility in rice (Kobayasi *et al.*, 2019), flower and tassel initiation in maize (Adishesha *et al.*, 2017), delayed flowering in *Arabidopsis thaliana* (Ward *et al.*, 2012) or on the pollinating insects *e.g.*, reduced pollinator visitation (Burkle and Runyon, 2016; Glenn *et al.*, 2018) and insect coordination and memories (Chen *et al.*, 2019; Stec and Kuszewska, 2020). As discussed in the earlier section of this review, increased ambient temperature affects the plant volatiles emission, modifying the composition of the volatiles and the quality of the floral cues (Farré-Armengol *et al.*, 2014; Räisänen *et al.*, 2008). The signal disruption leads to the breakdown of the recognition process, affecting the pollinator visitation rates (Farré-Armengol *et al.*, 2014; Jakobsen and Olsen, 1994).

The rate of rainfall was found to have minimal impacts on the population level of *E. kamerunicus* (Daud and Idris, 2016; Dhileepan, 1994; Latip *et al.*, 2018). In fact, the wet season is said to be better for *E. kamerunicus* breeding (Dhileepan, 1994). However, although its population was not affected by rainfall, the pollination efficiency of the pollinating weevil and the pollen viability of the crop was affected by rainfall (Gunawan *et al.*, 2020). In the event of rain, the number of pollen grains carried by the weevils was significantly reduced (Appiah and Agyei-Dwarko, 2013; Dhileepan, 1994). In some plant species, high rainfall may reduce the stigma pollen load, affecting the pollen deposition and leading to reduced pollination (Hendrix *et al.*, 1999). Hence, obtaining a further understanding of the impact of climate changes on the behaviour and fitness of the pollinating weevil is vital to enable the optimisation of crop pollination in the field.

Managing a Healthy Level of *E. kamerunicus* Population

This review has discussed both intrinsic and extrinsic factors that may have influenced the pollination efficiency of *E. kamerunicus*. Maintaining a sufficient weevil population in the field is critical for satisfactory fruit bunch production. It was also essential to provide enough resources for the weevils while maintaining a profitable fruit bunch production. Plant stress, which can impact physiological characteristics and volatile emissions

in the field, can be reduced with the use of good agricultural practices and land preparation. The following section of this article will further elaborate on the strategies to manage the population of *E. kamerunicus* in the field.

Minimising the usage of chemical insecticides.

In the oil palm plantation settings, most insects depend on relatively limited resources for food and shelter. Due to this, the management of insect pests also poses risks to beneficial insects, such as *E. kamerunicus*. *Tirathaba mundella* is one of the major insect pests of oil palm in peat areas in Sarawak, Malaysia (Mohamad *et al.*, 2017; Ming *et al.*, 2016; Sulaiman *et al.*, 2021). The moth was observed to be spending most of its initial phase of development in the female inflorescences and spent male inflorescences of oil palm (Mohamad *et al.*, 2017; Ming *et al.*, 2016; Prasetyo *et al.*, 2018; Yaakop and Abdul Manaf, 2015). The larvae of the pest are damaging the oil palm fruit bunch by scrapping the fruitlets and later boring holes in the mesocarp up to the kernel of the palm fruit (Lim, 2012). Prasetyo *et al.* (2018) and Lim (2012) observed that severe infestation of *Tirathaba* adversely affected the fruit set formation. Pest management requires insecticide application on the male inflorescences (Ming and Bong, 2017; Mohamad *et al.*, 2017; Prasetyo and Susanto, 2019; Prasetyo *et al.*, 2018). Thus, the application of insecticides, especially broad-spectrum chemicals, on the male inflorescences can potentially affect the population of the pollinating weevil (Ming and Bong, 2017; Prasetyo and Susanto, 2019). It was found that the active ingredients of 20% w/w dinotefuran, 80% w/w fipronil, and 5.5% w/w cypermethrin were able to inflict 79.52%, 87.91% and 44.82% mortality on adult *E. kamerunicus* (Ming and Bong, 2017). Some chemical insecticides were reported to have minimal impacts on the mortality of the weevils, such as chlorantraniliprole (Ming and Bong, 2017) and flubendiamide (Asib and Musli, 2020; Prasetyo and Susanto, 2019). Prasetyo and Susanto (2019) reported that the effects of both chlorantraniliprole and flubendiamide on *E. kamerunicus* were comparable to the control samples. Both recorded a mortality rate of 11% and 12% (one-day after treatment), respectively. Meanwhile, *E. kamerunicus* samples treated with water (control) recorded a mortality rate of 9%. Application of biological control agents, such as *Bacillus thuringiensis*, was also reported to reduce the larval population of *Tirathaba* spp. (Mohamad *et al.*, 2017; Prasetyo *et al.*, 2018). Prasetyo *et al.* (2018) and Ahmad *et al.* (2009) have reported that *B. thuringiensis*, which is mainly applied to control lepidopteran pests (*e.g.*, *Pteroma pendula*, *Metisa plana*, *Tirathaba* spp.), has minimal effect on the mortality of *E. kamerunicus*. *Bacillus thuringiensis* gave the longest median Lethal Time

(LT₅₀) to induce mortality in *E. kamerunicus* at 137 hr. Comparatively, cypermethrin gave a relatively short LT₅₀ of 17 hr (Asib and Musli, 2020). In addition to the application of the insecticides, alternative population control strategies, such as mass-trapping of adult *Tirathaba* moths, were also tested (Sulaiman *et al.*, 2021). These studies highlighted the importance of adopting properly-planned pest population controlling strategies while minimising the impacts on the population of beneficial insects in the oil palm ecosystem.

Preservation of biodiversity on pollination levels. Sustainable pest management strategies are vital to minimise the impacts on insect biodiversity and the sustainability of the crop itself. A study by Mayfield (2005) highlights the importance of insect biodiversity on oil palm yield. In the finding, although the areas of palm plantations close to the forest do not have greater floral-visitor diversity per visitation rate, the presence of understory vegetation in oil palm plantations helped increase the number of non-weevils pollinators in the area. Although maintaining understory complexity had no significant effects on fruit set formation, the increased insect biodiversity did not jeopardise the pollination and the population of the pollinator (Harianja *et al.*, 2019). In a biodiversity enrichment trial by Gerard *et al.* (2017), the plot with higher biodiversity had significantly higher yield than the control, even with lower planting density. Stand structural complexity can potentially contribute to establishing a more favourable microclimate (Donfack *et al.*, 2021; Tschardtke *et al.*, 2011), which also provides the benefits of biological pest control (Tschardtke *et al.*, 2011). This study highlights the importance of maintaining a healthy level of biodiversity in the oil palm plantation area by providing complementary pollination services, rendering natural pest population control while maintaining a satisfactory yield and productivity.

Weevil population supplementation. Management factors, effects of the surrounding landscape, and mass-replanting were identified as some of the main factors affecting the pollinating weevil populations and fruit set formations in oil palm plantations (Li *et al.*, 2019). In the areas where the mass-replanting of oil palm is conducted, rebuilding the pollinating weevil population usually requires time, resulting in poor fruit formations and a high rate of bunch abortions. In such areas, the practice of re-introduction and supplementing the weevil population is necessary. The weevil hatch and carry system are proven to be successful in improving fruit formation in the field. In Sabah, Malaysia, the application of the system was able to overcome the problem of occasional poor fruit set formation, with the trial field achieving an average

fruit set percentage between 58%-59% (Choong *et al.*, 2004). Whereas in Indonesia, applying a similar system has resulted in an improvement of fruit set between 15%-21% (Prasetyo *et al.*, 2014). The system utilised the spent spikelets of male inflorescences (containing weevil larvae) placed in a wooden shelter in the field. Upon hatching, the new cohorts of weevils will be puffed with viable pollen grains before release (Choong *et al.*, 2004; Prasetyo *et al.*, 2014). Variation of the hatchery systems is also suggested, and the result is quite promising (Genting Plantations Research Centre, 2018). The system, however, is not without its disadvantages. Some estates are questioning its practicality, citing the additional human resources and time required to source the proper stage of spent male inflorescences, then acquiring sufficient viable pollen grains to be applied on the hatchery, and the general maintenance of the hatchery. Improper application of the practice usually rendered the improvement brought about by the hatchery to be insignificant. Hence, the success of such a system depended on close supervision for precise application and cooperation between the management and field personnel.

Additionally, the introduction of pollinating the weevil population to the newly-opened oil palm plantation has been done previously, consequently improving the estate's yield (Prasetyo and Susanto, 2016). In the event/areas where a constant supply of post-anthesising male inflorescences is complex, supplementation of the weevil population in the field can also be achieved through rearing the weevils on an artificial diet. Studies to develop the artificial diet formulation for the laboratory rearing of the weevils were initiated *e.g.*, Zahari *et al.* (2019); Zulkefli *et al.* (2021), and further understanding of the nutritional contents of the natural feed was also reported (Zulkefli *et al.*, 2021).

Maintaining a sufficient number of male inflorescences in the field. The food source and breeding site availability for *E. kamerunicus* depends on the density of male inflorescence in the area. With the general aim to maximise yield without further expanding oil palm land use, the emphasis has shifted to developing high-yielding varieties (Kushairi *et al.*, 2010; Murphy, 2007; Soh, 2012). However, these varieties typically produce a more significant number of female inflorescences, which will later develop into fruit bunch. This scenario creates an imbalance in the sex ratio of the inflorescences and results in the lack of resources available for the pollinating weevil (Li *et al.*, 2019; Rao and Law, 1998). It was recommended that the DxP material be planted in every four rows of clonal material to supply sufficient resources to the pollinating weevil to overcome the imbalance in the inflorescence sex ratio (Kushairi *et al.*,

2010). Furthermore, the inducement of stress and unfavourable conditions are known to be causing the increased production of male inflorescences (Corley, 1976a). Agronomic practices such as over-pruning are shown to artificially induce the production of male inflorescence (Durand-Gasselín *et al.*, 1999) and reduce the rate of male inflorescences abortion (Legros *et al.*, 2009). As such, prudent management practices are necessary to ensure a sufficient number of male inflorescences are available for *E. kamerunicus* in the field.

What Next: A Way Forward

Several factors have been considered and elaborated on thoroughly in this review to solve the issues and problems regarding pollination efficiency. The committee has agreed that the following factors require further attention to solve the low fruit set problems; 1) Soil types, 2) planting materials, 3) weevil diseases and predators, 4) plant physiological and morphological stress, 5) estragole emission, and 6) sex ratio of the inflorescences. In addition, further understanding of the behaviour of the pollinating weevil is required. This includes the updated information on the fitness levels of *E. kamerunicus*, such as their searching ability and diel activity patterns. Based on the available literature and the research projects undertaken by the committee member, the majority of the committee members opined that for the time being, less priority should be given towards the idea of the importation of a fresh source of *E. kamerunicus* to increase the genetic pool or importation of entirely different pollinating insect species from the African region. Instead, the focus should be directed towards the studies related to the shortlisted factors discussed in this review.

CONCLUSION

Elaeidobius kamerunicus plays a vital role in the pollination of oil palm. Its introduction has brought a significant contribution to improving the oil palm fruit formation. It is difficult to discern a single factor that influences the pollination rate of oil palm. However, the shortlisted factors discussed in this review may be useful to the palm oil industry players and decision-makers in determining their priorities. Preserving healthy population levels of *E. kamerunicus* is essential to maintain the adequate pollination of oil palm. Frequent monitoring and census of the pollinator population have to be done. Practices that may jeopardise the population of pollinators should be avoided. Further understanding of the impacts of climate changes on the population, fitness and the behaviour of *E. kamerunicus* will be crucial.

In addition, a conclusive study on the genetic make-up of the current generation of *E. kamerunicus* in Malaysia is required. Effects of other factors such as VOCs emission (*i.e.*, estragole) and nematode parasitisation on weevil certainly require a more thorough understanding. General yield indicators such as bunch count, bunch weight, OER, and KER should be monitored regularly to ensure that fruit formation continues to be satisfactory. Proactive measures can be taken if any irregularities are detected. Some of the factors can be controlled with the provision of good agricultural practices and sound planning during land preparation. This includes the possibility of biodiversity enrichment in the oil palm plantation ecosystem, understory management, and soil management. A thorough understanding of factors affecting the pollination efficiency of *E. kamerunicus* will be instrumental in sustainably improving the productivity of the Malaysian palm oil industry.

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