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Ground based thermographic screening of bagworm (*Metisa plana* Walker) infestation in oil palm and identification of their growth stages

Mohd Najib Ahmad[1,2]*, Abdul Rashid Mohamed Shariff[2], Ishak Aris[2], Izhal Abdul Halin[2] & Ramle Moslim[1]

[1]Malaysian Palm Oil Board (MPOB), 6, Persiaran Institusi, Bandar Baru Bangi, 43000 Kajang, Selangor, Malaysia

[2]Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

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Bagworms (Lepidoptera: Psychidae) are one of the main species of vicious leaf-eating insect pests that affects oil palm plantations in Malaysia. A moderate bagworm attack of 10-50% leaf damage may cause 43% yield loss. In 2020, the economic loss due to the bagworm attack in Malaysia is estimated as RM 180 million. Hence, it is necessary to monitor closely the bagworm outbreak in infested areas. However, precise data collection with accuracy is a challenging task. In this context, we explored the possibility of using thermal infrared (TIR) cameras (T 440) for detection of bagworms and identification of bagworm growth stages at the infested areas for effective monitoring. The reflector method was applied to detect the reflected apparent temperature and emissivity of the bagworms using thermographic measurement techniques. The results have revealed that the bagworms from the 1st to 7th larval instar and pupal stages exhibit emissivity values ranging from 0.88 to 0.89. Two rounds of our observation have shown that the bagworms can be detected during evening and afternoon vision as compared to night, midnight and morning vision, with consideration of emissivity, solar radiation, and snapshot distance at a percentage accuracy of 74 and 85%, respectively. The classification of the larval and pupal stages was carried out by grouping the larval and pupal stages based on their real size; Group I: larval stage 1-3, Group II: larval stage 4-7; and Group III: pupal stage. Identification of the bagworm stages according to the classified group and the object led to differentiation between the larval stages from Gr. I, II, and III, with the per cent detection of 60, 84 and 89%, respectively. The results indicate that the thermographic imaging approach can be applied to detect bagworms, provided all conditions and time observation are taken into consideration. This thermographic technique deserves thorough testing and optimization for detection of bagworms in oil palm plantations.

Keywords: Emissivity, Infra Red thermography, Insect pests, IPM, TIR camera

Bagworm (Psychidae) is one of the major insect pests causing outbreaks in oil palm plantations. They are leaf eating caterpillars concealed within its carrot-shaped bag, which is constructed from bits of material from the plant upon which it feeds[1]. In fact, the bagworm at the larval stage survives inside the bag or case until the maturation stage. The shape and size of the case may vary from a narrow hose to an expansive sac depending upon the species[2]. Bagworm outbreaks are also associated with the dry season, and they feed more actively and spread faster in hot and dry weather[3]. The higher internal bag temperatures attributed to faster development time and boosted reproductive latent and abundance[4]. The economic impact of a moderate bagworm attack of 10-50% leaf damage is reported to result in 43% yield loss. In 2020, the yield loss due to the bagworm attack in Malaysia is estimated to be RM 180 million[5]. Integrated pest management (IPM) involves use of various methods such as biological agents, *Bacillus thuringiensis* (Bt), pheromone trapping, planting beneficial plants, and natural control by beneficial insects, and thereby works effective in controlling bagworm outbreaks in oil palm plantations[6]. For cotton mealybug, chemical control tactic is the last option of pest management in the IPM strategy[7].

In normal practice, physical census works better to monitor the infestation level. In large plantations, the census task involves consumption of labour, time and huge cost[8]. There is a need for an inexpensive system that could perform the task in an automated manner for a better, more accurate and precise data collection. In agricultural research study, researchers could solve difficult problems using thermal remote sensing technology or thermography. Acquisition of the image could be achieved by portable or handheld thermal sensors and thermal sensors that can be connected

*Correspondence:
E-Mail: mnajib@mpob.gov.my

with an optical set mounted on aircraft or a satellite[9]. It is possible to detect infected trees through thermal images by applying the thermal technique on field[10,11].

In this context, here, we tried to assess the effectiveness of ground based thermographic imaging to detect and identify bagworms at a specific distance range using a thermal infrared (TIR) camera. Furthermore, a series of experiments was carried out at different times to study the consistency of bagworm's temperatures when introduced by IR light source. Subsequently, the bagworm stages were also determined based on the real size measurement via the TIR application.

Materials and Methodology

Experimental set-up

The reflector method was applied to find targeted object, bagworms under thermographic measurement techniques[12]. Bagworms sample from all the larval instar and pupal stages of *Metisa plana* were collected and tested. Each experiment collected 30 data on apparent temperature and emissivity (sample size, n = 30). The workflow of this study is illustrated as follows (Scheme. 1);

Determination of reflected apparent temperature and emissivity

Once the sample (bagworm) was located at the selected area, the reflected apparent temperature was determined according to the reflector method. Then, a piece of electrical tape with high emissivity was placed on the sample. The image was focused, automatically adjusted, and frozen with the the thermal camera. At the same time, the Level and Span were adjusted to obtain the best brightness of the image and contrast. The emissivity of the tape was set at 0.97 and the tape's temperature was measured using the Spot measurement function. Then, the temperature obtained was recorded. The sample surface was pointed to the camera and the emissivity set-up was optimized until the reading temperature was similar to the the previous measurement. Finally, the emissivity of the sample was recorded[12].

Scheme. 1 — Flow chart of thermal imaging experiment

Image acquisition

The experiment was conducted in two rounds using a TIR camera, T 440 (FLIR, USA), with a spectral infrared range of 7.3–13 µM, at two different sites. The outdoor parameters, such as atmospheric temperature, humidity, and emissivity for the bagworm and background were obtained using a Hygro-thermometer (Extech, USA) (Suppl. Fig. S1. *All supplementary data are available only online along with the respective paper at NOPR repository at http://nopr.res.in*)[12]. A sunshine recorder was used to measure the number of hours of the day during which the sunshine was above a certain level (typically 200 W/m^2)[13] (Table 1). Each experiment captured and collected 50 thermal IR images at five different times (sample size, n = 250) and was repeated three times (total n=1050).

At the field site, the experiment was conducted on the ground by cutting down the infested fronds and laying them on the ground (Suppl. Fig. S2) to detect the presence and absence of bagworms. The 45° frond position or frond number 17 was selected to be cut down, as suggested by the standard operating procedure (SOP) for bagworm census[14,15]. Three oil palm trees and three palm leaflets per tree were selected and sampled for image acquisition. The first round of the experiment was conducted at Sg Buaya smallholdings, Banting, Selangor, Malaysia on 4th and 5th November 2016 with three different sampling times. The sampling periods were at 6.05 p.m. (evening), 10.30 p.m. (night) and 4.15 a.m. (5th November, morning). The second round of study was carried out at Kg Teluk Bunot, Banting, Selangor, Malaysia on 14th and 15 th November 2016 at two different sampling periods, i.e. 12.15 p.m. (afternoon) and 12.15 a.m. (15th November, midnight). The captured images were transferred into a computer and

Table 1 — The outdoor parameter set-up during the thermal imaging experiment

Round of trial/Date	Time	Sun radiation, Wm^{-2} (period)	Set parameters		
			Atmospheric temp. (°C)	Humidity (%)	Emissivity (ϵ)
First/ 4-5 Nov 2016	6.05 pm	470 (1 hour)	29±1.1	75	0.89±0.01
	10.30 pm	n/a	28±1.1	82	0.89±0.01
	4.15 am	n/a	27±1.0	82	0.89±0.01
Second/ 14-15 Nov 2016	12.15 pm	1487 (2 hours)	31±1.1	70	0.89±0.01
	12.15 am	n/a	25±1.2	92	0.89±0.01

[Note: emissivity for surroundings = 0.95[17]] further analysis using the FLIR Tools software version 5.8.

The study on the optimum distance for an effective snapshot was carried out at three different distances, 100, 75 and 50 cm as the objects or bagworms were too small in size, ranging 1.6-13.3 mm[13]. A measuring tape was used to measure the snapshot distance accurately. The effect of the snapshot distance was important due to the capability of the thermal camera to emit radiation towards the targeted objects, and also the TIR images consisted of pixel combinations. Basically, the snapshot or camera distance affected the percentage of the object/bagworm surface area which was included in every single pixel. The increase in the distance attributed to a larger area within each pixel. This condition contributed to the merging of neighbouring surface spots of diverse temperatures with longer distances, and it happened when the object's surface was thermally heterogeneous[16].

Identification of bagworm stages

The experiment on identification of bagworm growth stages was conducted using the same TIR camera, at Sg Buaya smallholdings, Banting, Selangor at 11 am on 18th April 2017. The outdoor parameters of atmospheric temperature, humidity, and emissivity were obtained using a Hygro-thermometer (Extech, USA)[12]. A measuring tape was used to measure the optimum distance during the snapshot. Each snapshot of the experiment captured 100 samples of the thermal IR images (sample size, n = 100). The infested frond with the multistage bagworms, *Metisa plana*, was cut down and the ground-based TIR snapshots were taken to measure the temperature of the object on the basis of three of classification groups: (i) 1st-3rd larval instar under Group I; (ii) 4th-7th larval instar under Group II; and (iii) Pupal stage under Group III[14,15].

Statistical analysis

All of the temperature data for the bagworms and fronds were analyzed using the Student's t-Test with two-tailed distributions to identify the significant difference and separability between the object and the surrounding temperatures. The data on the temperatures at different distances were analyzed, using one-way ANOVA and the means were separated by the Least Significant Difference (LSD) test at $P < 0.05$[6].

Results

Determination of the reflected apparent temperature and emissivity

Through the thermographic measurement technique, the reflected apparent temperature was measured based on an aluminium background temperature with three repetitions, and the average temperature recorded was at 31.7±0.02°C (Fig. 1A). This apparent temperature was further used to determine the emissivity of the bagworms. With 30 repetitions, it has been shown that the bagworms' surfaces exhibited emissivity values (Fig. 1B), approximately at 0.88±0.01 and 0.89±0.02 (Table 2). The measurement was conducted using all larval instars and pupal stages of the *Metisa plana*. Though, it was confirmed that the emissivity levels for different instar larva were similar, it was approximately 0.88±0.01 and 0.89±0.01. These values were further set and used during the thermal imaging

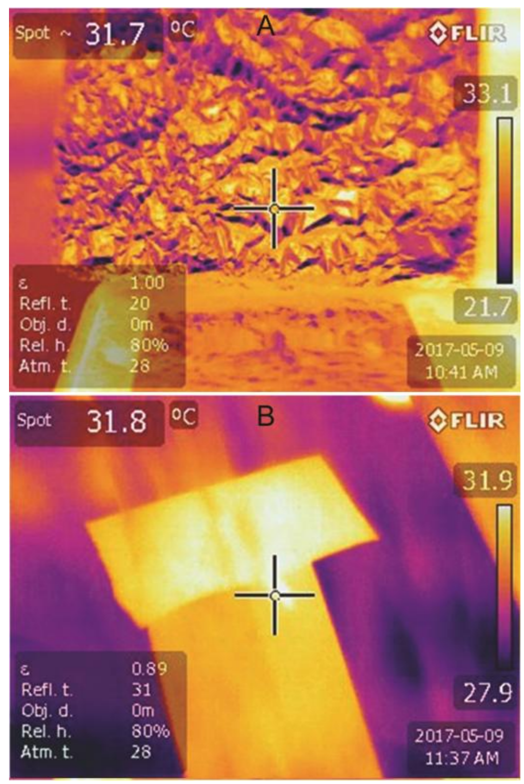

Fig. 1 — (A) Thermal image captured to determine apparent temperature; and (B) Measuring temperature of bagworm surface using the spot function

Table 2 — Reflected apparent temperatures and emissivity values of the bagworms

Bagworm stages	Reflected apparent temp. (°C)	Object surface/ Tape temp. (°C)	Emissivity (ϵ)
1st larval instar	30.0±1.1	31.5±1.3	0.88±0.01
2nd larval instar	29.9±1.1	32.7±1.1	0.88±0.01
3rd larval instar	31.7±1.3	34.1±1.0	0.89±0.01
4th larval instar	31.6±1.0	33.2±1.5	0.89±0.01
5th larval instar	31.7±1.1	31.6±1.3	0.89±0.01
6th larval instar	30.5±1.2	31.8±1.1	0.89±0.01
7th larval instar	31.0±1.1	33.0±1.0	0.89±0.01
Pupal stage	29.8±1.0	33.5±1.1	0.89±0.02

application for the bagworm detection. In this study, the mean emissivity value was set at the maximum point, 0.89±0.01, due to the factor of assessing the oil palm or plant temperature. Furthermore, the main target or result to be achieved from the TIR images was to observe the surface temperature of the insect bodies, compared to the surface temperature of the surroundings, which may have varied due to the effect of sunshine and humidity. In addition, the surface condition may also have affected emissivity when determining for accurate temperature measurements using TIR for the targeted objects[18].

Screening by TIR camera at different time period

The results of screening by thermal imaging at different time period viz., evening, night and morning using the FLIR thermal IR camera as first round of the experiment are shown in Figs 2 and 3 (A-C).

The present study resulted in almost similar colour images between the bagworms and fronds observed in Fig. 2 (A-C) at the optimum distance of 50 cm between the camera and the objects. According to Faye *et al*.[16], the object's body size is a crucial parameter to determine snapshot distance during the use of the TIR camera. In this study, the surface temperatures knowingly influenced the performance of the bagworms, especially when the heat transfer was led by conduction. The surface temperature was driven by solar radiation, whereby, it increased the eccentricity between the skin and the internal temperatures. However, for insects with dry-skin ectotherms and also low thermal torpor, the effects were not significant and remained low. Faye *et al*.[16] suggested that the snapshot distance to be the lowest possible, in order to obtain accurate and precise absolute surface temperatures. This condition anticipates the effect of lower atmosphere configuration (for outdoor) and pixel size coverage.

Based on the thermal imagery of all of the captured images, it was concluded that the bagworms' temperatures measured using spot target set up in the camera were slightly higher as compared to the fronds in all of the sessions of the experiment. The thermal imagery results were supported by the plotted graphs in Fig. 3 (A-C) where the bagworms' temperatures were recorded as higher than frond temperatures.

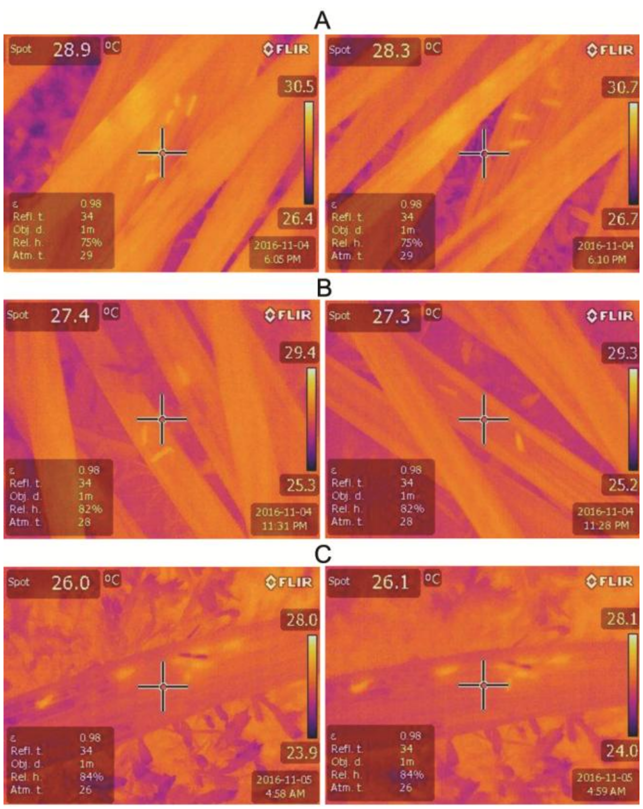

Fig. 2 — Thermal images of bagworms and the surrounding/front captured during (A) evening; (B) night; and (C) morning sessions

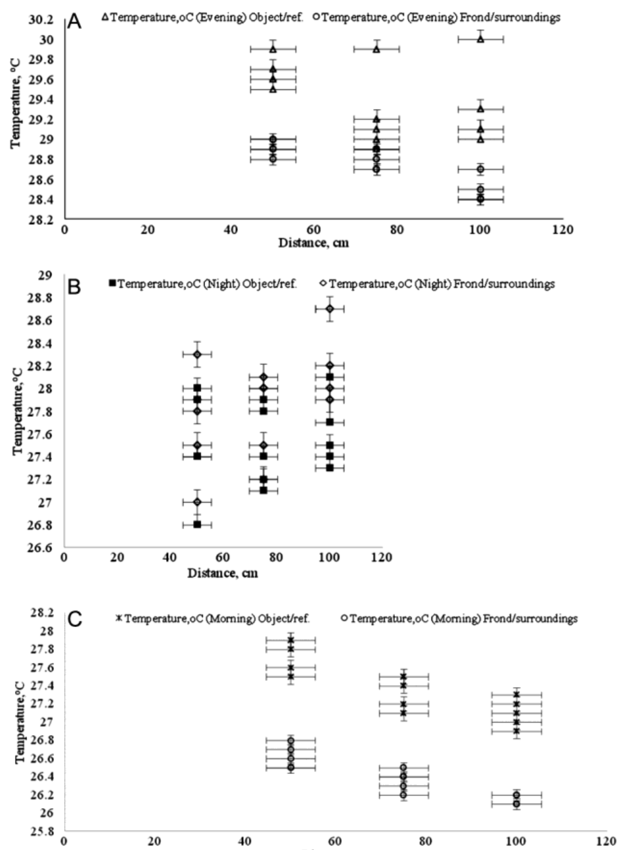

Fig. 3 — Temperature profile on distinguishing bagworm and frond subjected to different snapshot distances in the first experiment during (A) evening; (B) night; and (C) morning session

According to the Student's t-Test analysis, it was confirmed that the temperatures of the bagworms were significantly different as compared to the fronds' temperatures, $P < 0.05$.

The insect's body temperature attributed to the percentage of detection, whereby, bagworms detected during the evening and afternoon sessions resulted in higher detection accuracy, with 74 and 85% detection, respectively. Besides that, detection of the surface temperature was lower at night probably due to the thermal ecology effect of the bagworms, which regulated their body temperature via their abiotic environments[17,18]. These results could be the differences of the emissivity values between the bodies and their surroundings and, logically, may due to actual thermoregulation processes[19] (to maintain its core internal temperature) which make the bagworms warmer (for evening and afternoon sessions).

The detection percentage was calculated based on comparison between thermal image detection using TIR camera and manual observation, whereby, human counting was set as a basis counting result. The results of the bagworm detection at different sessions were shown to be significantly different at $P < 0.05$ after one-way ANOVA analysis using LSD test (Fig. 4).

The second round of the experiment was conducted at two different times, afternoon and midnight sessions, and the results are depicted in [Figs. 5 and 6 (A & B)]. In the afternoon session, the bagworms were clearly seen in false colours as compared to the fronds during afternoon session. Furthermore, same results were obtained as in the first round of the experiment, whereby, the bagworms' temperatures were found significantly high as compared to the fronds' temperature (Fig. 6A).

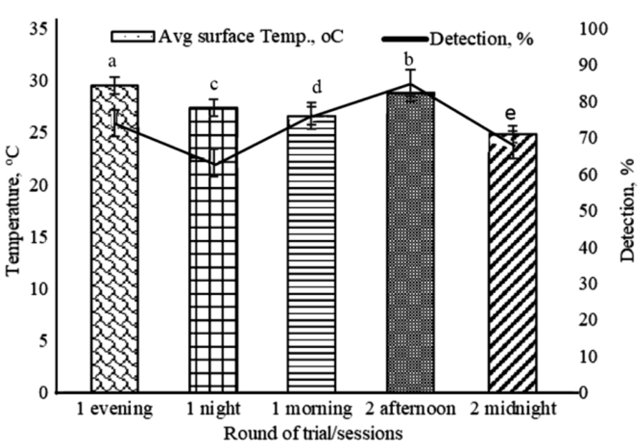

Fig. 4 — Body temperature profile and per cent detection of bagworms at camera distance of 50 cm at different sessions. [A bar with different letters was significantly different at $P < 0.05$ after one-way ANOVA analysis using LSD test]

The midnight session snapshots showed the bagworms to be quite blurry and difficult to detect during midnight session (Fig. 5B). However, similar results were obtained as compared to the first round of the experiment, where the bagworms' temperatures were significantly higher as compared to the fronds' temperatures (Fig 6B). These significantly different results were proven by the Student's t-Test analysis where $P < 0.05$.

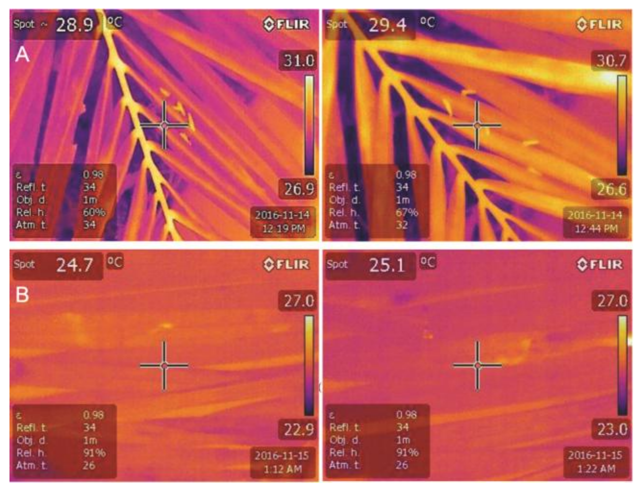

Fig. 5 — Detection of bagworms using TIR camera during (A) afternoon; and (B) midnight session.

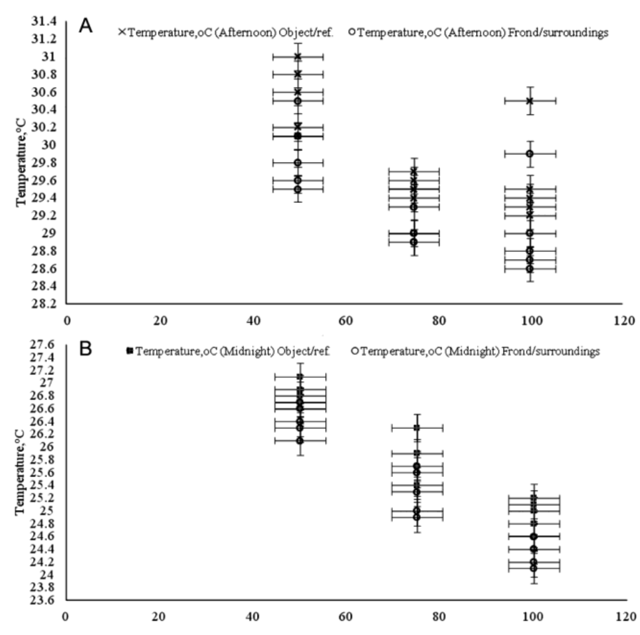

Fig. 6 — Temperature profile to distinguish between bagworm and frond subjected to different snapshot distances in the second experiment during (A) afternoon; and (B) session

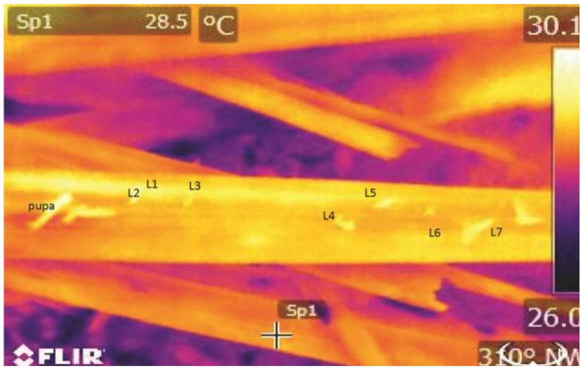

Fig. 7 — Identification and distinguishing of the bagworm stages based on temperature observation via thermal imaging. Note: L1: larval stage 1, L2: larval stage 2, L3: larval stage 3, L4: larval stage 4, L5: larval stage 5, L6: larval stage 6, and L7: larval stage 7

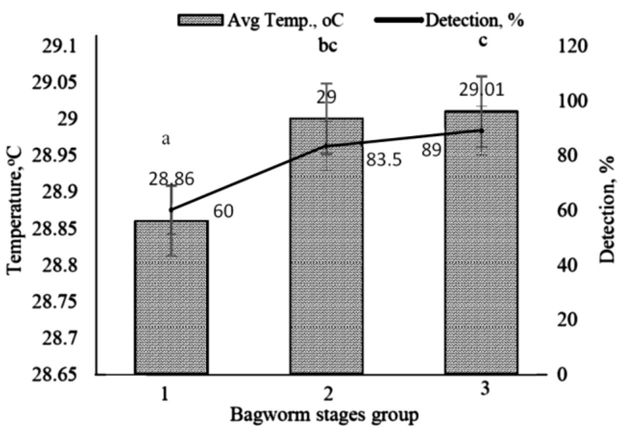

Fig. 8 — Detection percentage and temperature correlation between three groups of bagworms stages. [Gr. I: L1-L3, Gr. II: L4-L7, and Gr. III: Pupa. [A bar with different letters was significantly different at P <0.05 after one-way ANOVA analysis using LSD test]

Identification and detection of the bagworm stages based on the temperature gradient

The experiment on thermal imaging to identify bagworm sizes and stages was conducted at 11 a.m. at Sg Buaya smallholdings, Banting, Selangor. The outdoor parameters of the atmospheric temperature, humidity, and emissivity were set at 28±0.02℃, 80%, and 0.89, respectively. The results obtained are illustrated in Fig. 7. It could be observed that the size of the 7th larval instar of the bagworm *Metisa plana* was close to the size of the pupa. Moreover, the 1st larval instar of the *M. plana* was obviously too small to be observed clearly via the thermal camera although the zooming function was applied. According to the Student's t-Test analysis, the bagworm stages of Gr. I (L1-L3) were significantly different from the two other groups, Gr. II (L4-L7) and Gr. III (pupa), with P <0.05 (P = 5.1×10^{-7}).

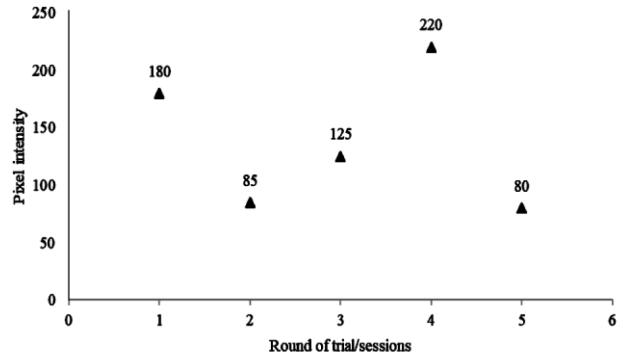

Fig. 9 — Responsive pixels during TIR imaging of bagworms. [x-axis 1: Evening session 1; 2: Night session 1; 3: Morning session 1; 4: Afternoon session 2; and 5: Midnight session 2]

However, Gr.II was not significantly different from Gr. III, with P <0.05 (P = 0.88). The thermal imaging technique was able to differentiate between the larval and pupal stages (Gr. I), however, the object temperature for Gr. II (L4-L7) was not significantly different from the pupal stages (Gr. III) (Fig. 8). Figure 9 shows that the most responsive pixels were detected at pixel intensity ranging 180-220 based on light source of the FLIR TIR camera and after image analysis using FLIR software, which happened during evening and afternoon snapshot session.

Discussion

Based on the thermographic measurement, it is important to know the reflected apparent temperature, which measured the radiation or emission reflected in the bagworms. Furthermore, the significant emissivity difference between the bagworm and aluminium, exhibited a high contrast between the bagworm and the background[20]. Generally, the emissivity for any object material is in the range 0.1-0.95. The radiation is initiated from the surroundings or environment and, subsequently, it is reflected in the object. The absorption of the atmosphere also influenced the radiation strength[14]. In fact, the solar radiation levels attributed a significant impact on the body surface temperature of the bagworms. A high solar radiation level (Table 1) contributed to the high surface temperature detection of the bagworm's body. However, at the oil palm field, the effect of solar radiation could be minimized by canopy shading during the ground-based TIR shoot.

From the results of the thermographic imaging experiment (Table 2), it was clearly observed that the snapshot distance played a crucial role to determine the viability of the thermal IR imaging. According to

Simone *et al*.[21], a standardized placement of the camera at similar viewing distances each time the snapshot is taken would ensure that the information obtained is comparable for all of the different thermographic images. Based on the optimisation of the distance between the camera and the bagworms, it was revealed that 50 cm is the best viewing distance as compared to 75 and 100 cm. The viewing distance, 50 cm was apt to capture the sharpest images. Ball and Pinkerton[22] reported that a constant viewing distance on the objects is applied by way of the built-in software inside the camera, however, in reality and several cases, the distance could be extended by an extra hundred metres and with the viewing distance across an image always varying.

The captured thermographic image of the bagworms for the first round of the experiment [(Fig. 2 (A-C)] were similar as obtained for the second round of the experiment (Fig. 5 A,B). The bagworms could not be easily differentiated in false colour mode, whereby, this is because of the sharp and clear object images were only detected during the afternoon and evening sessions. Basically, when the first round of the experiment was carried out during the evening, the false colour of the frond was a slightly yellowish in colour, with the temperature being recorded at an average of 29.0±0.02°C. Meanwhile, the bagworms or targeted objects were observed in a full yellowish false color, with an average temperature being recorded at 29.5±0.02°C (Figs 2A & 3A). With the night vision, a yellowish false colour of the frond was observed with an average temperature of 27.2±0.02°C and a bright yellowish false colour was observed for the bagworm images, with an average temperature of 27.4±0.02°C (Figs 2B & 3B). However, with the morning vision, the frond false colour was darker, with the lowest average temperature at 26.3±0.02°C. As for the bagworm image, the yellowish false colour was detected, with an average temperature of 26.6±0.02°C (Figs 2C & 3C). From Fig. 4, detection accuracy of the surface temperature of the bagworms appears to be lower at night, midnight and morning probably due to the thermal ecological effect of the bagworms, which regulate the body temperature through their abiotic environments[19]. These results also could be the differences of the emissivity values between the bodies and their surroundings. Another round of the experiment conducted during the afternoon vision (Figs 5A & 6A) gave a better result as compared to the evening vision in the first round of the experiment. Besides that, the midnight vision (Figs 5B & 6B) was also resulted in the same thermographic images as compared to the morning and night vision in the first round of the experiment.

In this study, it was revealed that by applying thermography imaging on infected fronds, the bagworm population could be detected based on the slightly higher bagworm temperatures as compared to the frond's temperature. This result could only be applied during evening and afternoon sessions only. During evening and afternoon, the actual thermoregulation processes (to maintain its core internal temperature) make the bagworms warmer and could be detected via thermal IR camera. In some cases, the frond temperature was approximately similar to the bagworm temperature due to the water stress caused by the bagworm attack. During the hot season, the bagworms became active due to the water stress, whereby they moved and consumed aggressively to gain water. Furthermore, TIR imaging acquisition was usually started after five minutes of cutting and laying the fronds on the ground. This is a normal time interval for TIR camera set up. Then, in some thermal acquisition, the higher bagworm temperature was detected due to heat transfer from human fingers to their body (surface temperature), which happened during repositioning of the bagworms on the fronds (they moved everywhere during the snapshot to other parts of the fronds). According to Faye *et al*.[16], the same irradiance conditions during the snapshot should be considered and proceeded by recording the global solar radiation.

Indeed, the bagworms (Lepidoptera: Psychidae) are categorized as ectothermic insects which rely on their surrounding environment to attain their thermal performance[19]. Ectotherms refer to invertebrates, amphibians, fish, and reptiles, who adjust their internal body temperature, $T_{B,}$ externally via characteristic mechanisms to suit heat exchange in their bodies with the surrounding[15]. In fact, in normal body temperature, amount of heat developed in the body is maintained by the complementary with the amount shifted or exposed to the environment[23]. According to Maliszewska & Tegowska[24] experience in against potato beetles control, Colorado potato beetles control, when intoxicated beetles change their thermal preferences succeeding insecticide exposure, their body temperature also changed, following exposure temperature. Their internal physiological sources of heat are relatively small or quite negligible in controlling the body temperature. Therefore, ectotherms regulate their body temperature by making use of their abiotic environments and they face the environmental conditions by taking advantage of the spatiotemporal variability. Thus, ectotherms thermoregulate throughout a combination of physiological and behavioural mechanisms that allow them to deal with the spatial and temporal heterogeneity of their environments (e.g., to avoid the risk of thermal death or to maximize diverse performance traits)[19]. According to other study on other insect larvae done by Hoffmann et al.[25], the goat moth larvae, *Cossus cossus* cannot be traced using infrared thermography (IRT) in solid wood due to adaption to ambient temperature and surroundings, subsequently, minimal surface temperature differences was recorded through activation energy and larval motion.

Furthermore, based on the bagworms characteristics, it is known that the larval and pupal stage of the bagworms are fully covered or wrapped with ‘bags’. The bagworm family (Lepidoptera: Psychidae) with 1000 species, complete their larval stages inside a self-enclosing bag or case. Referring to this characteristic, the surface temperature of the bagworms may increase compared to surrounding due to the combination of the bag and insect’s body temperature, which could hold a certain level of heat. As reported by Lillesand *et al*.[9] and Soroker *et al*.[26], in the case of a red palm weevil (RPW) attack on palm trees, the insects could cause water stress and, subsequently, it was clarified by the higher canopy temperature of the palm trees. Furthermore, the new interest in thermal sensors has been linked to the measurement of evapotranspiration parameters and the usage of plant canopy temperatures that conclude with water stress and crop yield[27]. Besides that, in temperature measurements using IR thermography (IRT), an accurate calculation of the emissivity of the targeted object and the reflected temperature could influence the temperature observation. The emissivity shows that an amount of radiation is released from the object related to the blackbody’s emission at a similar temperature[11,28].

It was found that the smallest stage of the bagworm or the 1st larval instar was difficult to be traced with thermal imaging. However, the other larval instars (L2-L7) and the pupal stage were easy and practical to be identified using the TIR camera. In this situation, a normal measurement technique of the larval size needed to be carried out for precise and accurate identification. In order to identify the bagworm stages correctly, the bagworm temperature of the region of interest (RoI) must be measured accurately to obtain high percentage of detection. The small size of Gr. 1 bagworm led to low detection, 60% as compared to Gr. II and III bagworms, with 83.5 and 89% detection, respectively. This condition occurred due to low heat transfer generated from small bagworms or larvae stage 1-3, whilst the other two groups have big body size, whereby high heat transmission were generated from them. Subsequently, the Gr. II and III were successfully detected using TIR camera. According to Ruben *et al*.[11], in normal practice, the IR images contain information on the target object, plus the surroundings. The image identification needs to be clarified prior to obtaining the target object temperature. As a support, Ruben *et al*.[11] reported that the emissivity calculation may also not be applicable when handling or operating small sized and distant objects. Besides that, this result may also be influenced by the change in camera position at different angles and distances during the capturing the snapshot. Simone et al.[21] has reported that two different angles, 70° and 110°, were the most practical positions for the thermal camera positioning to capture an effective region of interest (RoI). Furthermore, the suitability and performance of the TIR relies on the thermal sensitivity, image resolution, and scan speed[12,13]. Thus, these factors were influencing the result of the identification of the bagworm stages. Indeed, the timing of the life stages of the insects depends on the asymmetrical distribution of thermal responses[29,30] and their demographic consequences[31,32]. According to Hagstrum & Miliken[33], the egg, larval and pupal stage durations of nine species of stored product, Coleoptera, observed at 27°C were averaged from 15, 66 and 19% of the total developmental period, respectively, with moisture levels lower than 12%. When the moisture levels were above 12%, the stage durations were averaged from 12, 72 and 15% of the total developmental period, respectively. The same percentages were recorded at other temperatures, ranging 20-35°C. To be precise, different species and stages of the insects had different developmental periods, although they were investigated in similar environments.

The results (Fig. 9) have shown that the most responsive pixels in false colour mode detected during evening and afternoon snapshot were 180 and 220, respectively and gave better detection results. These results were similar as reported by Najib *et al*.[34] which has generated positive results to detect live and dead pupae by averaging pixel counts in IR vision. According to Deepika *et al*.[35], heat emissivity information is conveyed through all pixels in the TIR images, which is a reflexive contact-free modality. The pixel reliability can be improved by reducing random noise through averaging images as the images acquired at the constant condition[36].

Conclusion

The TIR imaging technique has been adapted to detect bagworms with anticipation of the shooting distance between the bagworms and the TIR camera, due to the characteristic factor of ectothermal insects. Through selective times or different snapshot sessions study, the TIR camera observation showed that the bagworms can be detected during evening and afternoon vision as compared to night, midnight and morning vision, with consideration of emissivity, solar radiation, and snapshot distance at percentage accuracy of 74 and 85%, respectively, whereby, the most responsive pixels in false color mode detected during evening and afternoon snapshot were 180 and 220, respectively and gave better detection results. Identification of the bagworm stages based on the classified groups and object temperature was able to distinguish between the larval stages from Gr. I, Gr. II, and the pupal from Gr. III, with the percent detection of 60, 84 and 89%, respectively. The results have revealed that the thermal imaging concept for monitoring of bagworms population requires extra repetition to increase visibility because the thermal image gave low pixel intensity for object detection as compared to RGB imagery, especially during object identification in night, midnight and morning which exhibited quite similar colour with background. Furthermore, the advancement of thermographic imaging camera which can be integrated with drones can be explored and uses for thermal imagery detection of insects in the field.

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Conflict of interest

Authors declare no competing interests.

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