

FIELD-BASED EVALUATION OF MEALYBUG-SOOTY MOULD DYNAMICS IN OIL PALM

SEBREY JEN SOMPIT^{1,2}; MOHD NOZULAI NORDIN³; MUHAMMAD DZULHELMI MUHAMMAD NASIR⁴; CIK MOHD RIZUAN ZAINAL ABIDIN⁴; MARK WONG KUI LIANG^{1,5}; BELLERICTER BINJAMIN¹; DK NORHAJIJAH AK MOHIDDIN¹; SALUMIAH MIJIN¹; CLAMENT CHIN FUI SEUNG¹ and SUZAN BENEDICK^{1*}

ABSTRACT

Mealybugs (MB) (*Pseudococcidae*) are sap-sucking insects that promote the growth of sooty mould (SM) through honeydew secretion, posing an emerging threat to oil palm (*Elaeis guineensis* Jacq.) productivity in Sabah, Malaysia. This study quantified the field-level relationship between MB infestation and SM colonisation in oil palm plantations and developed a standardised Mealybug-Sooty Mould Severity Index (MSI) for field surveillance. Study was conducted across four plantation blocks in the FGV Sahabat Region from February to September 2025, representing a gradient of palm age: Young (1–3 years), intermediate (4–6 years) and mature (13 years). A total of 120 palms were assessed, with fronds examined at upper, middle and lower canopy levels using binoculars to detect MB colonies and associated SM. Mature palms exhibited the most severe infestations, with a strong positive correlation between MB density and SM colonisation. MSI values increased with palm age and were consistently highest in the lower canopy. These findings highlight the close linkage between pest infestation and fungal development and emphasise the importance of field-based surveillance to support timely intervention within integrated pest management programmes.

Keywords: index of severity, mealybugs, oil palm, sooty mould.

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INTRODUCTION

Oil palm is one of the most important crops in Southeast Asia, particularly in Malaysia, where it contributes substantially to national income, rural livelihoods, and the global supply of vegetable oil (Parveez et al., 2025). However, the sustainability and productivity of oil palm plantations are increasingly threatened by pest infestations and their associated secondary effects, which disrupt physiological processes and reduce overall yield.

Among the sap-sucking pests affecting tropical crops, the coconut mealybug (MB) *Nipaecoccus nipae* (Hemiptera: Pseudococcidae) has emerged as a particularly damaging species in Sabah (Mohd Zin et al., 2023; Pacific Pests, Pathogens & Weeds, 2020). Its phloem-feeding behaviour depletes plant resources and results in the excretion of honeydew, a carbohydrate-rich substrate that promotes the proliferation of sooty mould (SM) fungi. These fungi form dense, black mycelial layers on leaf and fruit

¹ Faculty of Sustainable Agriculture, Universiti Malaysia Sabah, Locked Bag No. 3, 90509 Sandakan, Sabah, Malaysia.

² Sabah Zone Department, FGV Agri Services Sdn. Bhd., Lot 2, Ground Floor, iPeak Business Centre, MDLD 8992, Jalan Lahad Datu–Tungku, 91110 Lahad Datu, Sabah, Malaysia.

³ Agronomy & Smart Farming Department, FGV R&D Sdn. Bhd., Stesen Penyelidikan Sabah, Peti Surat 02, Cenderawasih, 91150 Lahad Datu, Sabah, Malaysia.

⁴ IPM & Wildlife Coexistence Department, FGV R&D Sdn. Bhd., Tun Abdul Razak Agricultural Research Centre, 27000 Jerantut, Pahang, Malaysia.

⁵ Pest Management Unit, FGV R&D Sdn. Bhd., Stesen Penyelidikan Sabah, Peti Surat 02, Cenderawasih, 91150 Lahad Datu, Sabah, Malaysia.

* Corresponding author e-mail: suzanben@ums.edu.my

surfaces, impairing photosynthesis, transpiration and fruit development, ultimately compromising plant vigour and complicating harvesting operations (Borkakati et al., 2024; Insausti et al., 2015; Subramanian et al., 2021).

The *N. nipae* is highly polyphagous, recorded on more than 40 plant families worldwide (Espinosa et al., 2009), underscoring its invasive potential and complicating control efforts. In Sabah, its spread is facilitated by favourable climatic conditions and the apparent absence of effective natural enemies, enabling rapid population build-up and movement across agroecosystems. The synergistic interaction between MB infestation and SM colonisation presents diagnostic and management challenges, particularly in large-scale plantation systems where early detection and severity assessment are essential for timely intervention.

Despite increasing reports of mealybug-sooty mould complexes in oil palm plantations, standardised field-based tools for quantifying severity and understanding the ecological dynamics of their co-occurrence remain limited. Most existing studies have focused on pest identification, fungal taxonomy, or general symptom descriptions and relatively few have incorporated severity indices that can support operational decision-making and routine surveillance (Mohd Zin et al., 2023). This absence of standardised assessment frameworks limits the ability of field personnel and researchers to compare infestation levels across field sites, detect early escalation and implement timely interventions.

The present study was designed with two main objectives. The first was to quantify the field-level relationship between MB infestation and SM colonisation in oil palm plantations. The second was to develop and validate a standardised Mealybug-Sooty Mould Severity Index (MSI) for use in field surveillance. By applying the MSI across a gradient of palm ages and canopy levels, the study provides field-based insights into infestation patterns and the ecological linkage between MB abundance and SM development. In addition, the MSI addresses limitations of existing qualitative rating systems, which typically assess pest presence or fungal symptoms in isolation and lack consistency across canopy strata. The proposed index offers a standardised, canopy-explicit metric that jointly quantifies MB infestation and SM development, enabling more comparable and ecologically meaningful assessments. The findings are intended to support field personnel and researchers in strengthening pest surveillance, refining integrated pest management strategies and advancing ecological understanding of pest-fungal interactions within oil palm ecosystems.

MATERIALS AND METHODS

Location of Study Site

The field study was conducted across four oil palm plantation blocks within FGV Plantations, Sahabat, Lahad Datu, Sabah, Malaysia, an extensive monoculture landscape characterised by high production intensity and notable ecological variability. Field sampling and MSI validation were carried out over eight months from February to September 2025, involving a total of 120 palms. The selected sites included FGV PM Sahabat 43 North (Location 1; 5° 19' 8.36" N, 119° 3' 28.98" E), which comprised young palms aged 1–3 years; FGV PM Sahabat 33 East (Location 2; 5° 20' 4.49" N, 119° 11' 53.63" E), containing intermediate-aged palms of 4–6 years; and two mature blocks, FGV PM Sahabat 9 West (Location 3; 5° 5' 51.50" N, 118° 57' 36.40" E) and FGV PM Sahabat 11 (Location 4; 5° 9' 27.90" N, 119° 8' 10.54" E) (Figure 1), both consisting of palms aged 13 years. These locations were strategically selected to represent a gradient of palm maturity and canopy strata, enabling comparative analysis of MB infestation and associated SM colonisation across different growth stages.

Collection of Data

Data on MB infestation and SM colonisation were obtained through systematic field observations conducted across three defined canopy levels of oil palm: Upper (fronds 1–16), middle (fronds 17–32), and lower (fronds 33–48), following an observation protocol adapted from Mohd Zin et al. (2023). At each study site, fronds were visually examined using an SA202 binocular telescope (SVBONY 10 × 42 Roof Prism, FMC Coating, China) to detect the presence of MB colonies and associated SM growth. Observations focused on identifying fronds exhibiting clear, active signs of pest colonisation and fungal development, with infestation presence recorded separately for each canopy level. Only fronds with unambiguous evidence of MB activity or SM colonisation were included in the dataset to ensure consistency and reliability in severity scoring and subsequent correlation analyses.

Research Experimental Design

A total of 120 palms were assessed, with 30 palms sampled at each location. At every site, palms were selected using a systematic sampling strategy to ensure unbiased and consistent coverage of the plantation area. Each location was subdivided into six replicate sampling plots and five palms per plot were selected by sampling every n th palm along a planting row. To maintain spatial independence among replicates and capture within-location



Figure 1. Aerial view of study sites in FGV Sahabat, Lahad Datu, Sabah, showing visible sooty mould infestation across oil palm blocks of varying age. (a) FGV PM Sahabat 42 North (Location 1), comprising young palms aged 1–3 years; (b) FGV PM Sahabat 33 East (Location 2), with intermediate-aged palms of 4–6 years; and two mature blocks, (c) FGV PM Sahabat 9 West (Location 3) and (d) FGV PM Sahabat 11 (Location 4), both consisting of palms aged 13 years.

heterogeneity, the distance between sampling plots was standardised at approximately 100 m, equivalent to roughly 11 palms. This spacing reduced the likelihood that palms in different plots experienced the same localised pest pressure or micro-environmental conditions. All four locations were managed under comparable agronomic practices, including fertilisation, pruning and ground-vegetation control, and field assessments were conducted under similar weather conditions to minimise environmental variability during data collection. This sampling design ensured that observations were representative of each plantation location, provided adequate replication within sites and offered a robust basis for comparing infestation severity across palm age classes and spatial zones.

Mealybug-Sooty Mould Severity Index (MSI)

Infestation severity was assessed using a frond-based evaluation system in which each palm was examined for the presence or absence of MB colonies and associated SM. For every palm, the total number of fronds and the number of infested or colonised fronds were recorded. The proportion of affected fronds was then used to classify each palm into discrete severity categories. This proportional approach aligns with established principles in plant

disease epidemiology, where percentage-based thresholds are widely applied to represent biologically meaningful transitions in host damage and disease intensity (Campbell & Madden, 1990; Madden et al., 2007; Nutter et al., 1991).

To ensure consistent interpretation of canopy involvement, the number of infested fronds per palm was converted into percentage thresholds based on an average of 48 fronds per palm (Table 1). Five severity categories were defined, beginning with a baseline of 0% representing the absence of MB infestation or SM colonisation. The remaining categories followed quartile-based thresholds commonly used in pest and disease severity scales. These thresholds reflected clear biological transitions observed in the field. Palms with 1%–25% infestation typically exhibited localised colonies with minimal canopy impact, whereas palms exceeding 76% infestation showed extensive MB presence accompanied by heavy SM coverage.

To integrate the categorical severity ratings into a continuous metric, each severity class was assigned a weight equal to the midpoint of its infestation range (Table 1). Midpoint-based weighting is widely used in severity index construction because it provides a stable representation of class severity and reduces bias associated with extreme values (Jeger & Viljanen-Rollinson, 2001; Madden et al., 2007).

TABLE 1. FIELD INDEX GUIDE FOR MSI SEVERITY CATEGORIES

Index value (number of infested fronds per palm)	Infestation threshold (% of fronds infested)	Weightage	Severity classification
0	0	0.000	None
1–12	1–25	0.125	Low
13–24	26–50	0.375	Moderate
25–36	51–75	0.625	High
37–48	> 76	1.000	Critical

The MSI was calculated using Equation (1):

$$MSI = \frac{\sum (n_i \cdot w_i)}{N} \quad (1)$$

where, n_i is a number of palms in severity category i , w_i is a weight assigned to severity category i , N is a total number of palms assessed. The resulting index ranges from 0 (no infestation) to 1 (critical), providing a standardised metric for comparing infestation levels across canopy strata and palm age groups.

Statistical Analysis

A one-way analysis of variance (ANOVA) was used to evaluate whether infestation severity differed significantly across locations, palm age categories, and canopy levels. Prior to analysis, the data were assessed for normality using the Shapiro-Wilk test and for homogeneity of variances using Levene's test, both of which confirmed that the assumptions for ANOVA were met. Post hoc comparisons were conducted using Tukey's HSD (Tukey-b) to identify significant pairwise differences among groups. Pearson's correlation analysis was performed to assess the relationship between MB infestation and SM occurrence. All inferential statistical analyses were carried out in SPSS version 27 (IBM Corp, 2020), while Microsoft Excel was used solely for data entry and organisation. Statistical significance was set at $p < 0.05$.

RESULTS AND DISCUSSION

Frequency of Fronds Infested by Mealybugs (MB) and Sooty Mould (SM) According to Oil Palm Tree Age Categories

Analysis of mealybug infestation frequency across palm age groups and canopy levels revealed clear patterns in pest distribution (Table 2). Young palms (1–3 years) at Location 1 showed the lowest infestation counts across all canopy levels, indicating limited

colonisation during early developmental stages. Intermediate-aged palms (4–6 years) at Location 2 exhibited moderate infestation levels, whereas mature palms (13 years) at Locations 3 and 4 recorded substantially higher frequencies. These findings suggest that older palms provide more favourable microhabitats for MB establishment and persistence. Across all locations, infestation was most pronounced in the lower canopy (Level 3: Fronds 33–48), followed by the middle (Level 2) and upper canopy (Level 1), with total infested frond counts of 1,524, 1,252 and 525, respectively. Notably, Location 4 exhibited equal infestation frequencies in Levels 2 and 3, indicating saturation across the mid- and lower-canopy zones.

The SM colonisation showed similar trends (Table 2), with minimal infestation in young palms at Location 1 (1 frond in the upper canopy, 103 fronds in the middle; 110 fronds in the lower canopy). Intermediate-aged palms at Location 2 displayed increased colonisation, particularly in the lower canopy (295 fronds). Mature palms at Locations 3 and 4 recorded the highest frequencies, with Location 4 reaching saturation in both middle and lower canopy levels (480 fronds each). Consistent with MB patterns, the lower canopy harboured the highest number of SM-affected fronds (1,353), followed by the middle (1,178) and upper canopy (482).

This stratified pattern aligns with previous observations indicating that the lower canopy offers a more favourable microclimate for pest persistence, characterised by higher humidity, reduced light penetration and longer leaf retention, which together support MB colonisation and honeydew accumulation (Mohd Zin et al., 2023). Likewise, the more uniform distribution in mature palms reflects earlier reports of vertical spread and sustained infestation driven by continuous MB activity and microclimatic conditions that promote SM development across canopy layers. These interpretations are based on established findings and field-level observations and while consistent with known ecological mechanisms, they warrant further study to verify the underlying drivers within the present system.

TABLE 2. FREQUENCY OF MEALYBUG (MB) INFESTATION AND SOOTY MOULD (SM) COLONISATION ACROSS CANOPY STRATA AND LOCATIONS

Location	Total number of infested fronds					
	MB			SM		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
1	12	143	219	1	103	110
2	16	198	356	15	168	295
3	221	431	469	199	427	468
4	276	480	480	267	480	480
Total	525	1,252	1,524	482	1,178	1,353

Note: Location 1: FGV PM Sahabat 43 North (Trees aged 1–3 years), Location 2: FGV PM Sahabat 33 East (Trees aged 4–6 years), Location 3: FGV PM Sahabat 9 West (Trees aged 13 years) and Location 4: FGV PM Sahabat 11 (Trees aged 13 years). Frond levels are defined as follows: Level 1 – upper canopy (fronds 1–16), Level 2 – middle canopy (fronds 17–32) and Level 3 – lower canopy (fronds 33–48).

Quantifying the Field-Level Relationship Between Mealybug (MB) Infestation and Sooty Mould (SM) Colonisation

A one-way ANOVA showed significant differences in MB infestation across the four locations (Table 3; $F_{3,359} = 74.46$, $p < 0.001$), suggesting that infestation severity was higher in locations with more mature palm trees. Similarly, a one-way ANOVA showed significant differences in SM infestation across the four locations (Table 3; $F_{3,359} = 111.51$, $p < 0.001$), indicating that fungal colonisation was higher in locations with more mature palm trees. Post hoc comparisons (Tukey's HSD) in Table 3 revealed clear differences among locations, with young palms (1–3 years old) from Location 1 showing the lowest mean infestation levels for both MB and SM. Intermediate-aged palms (4–6 years old) from Location 2 showed moderate levels, whereas mature palms (13 years old) from Locations 3 and 4 had the highest infestation and colonisation intensities.

The MB infestation showed a clear age-related gradient across locations. Young palms at Location 1 recorded the lowest mean infestation (4.16), significantly lower than all other sites. Location 2 exhibited a moderate increase (6.33),

while mature palms at Locations 3 and 4 showed the highest infestation levels (12.46 and 13.73), with no significant difference between them. These results demonstrate a strong association between palm age and MB severity, with older palms supporting substantially higher levels of colonisation. Several ecological and physiological factors may contribute to this pattern. Mature palms are known to accumulate greater carbohydrate reserves and contain higher concentrations of soluble sugars such as glucose, sucrose and fructose (Henson et al., 1999; Kosugi et al., 2010). Long-term nutrient management practices involving nitrogen, potassium and magnesium further enhance photosynthesis and sugar synthesis (Chew et al., 1996). While essential for productivity, these conditions may inadvertently favour sap-feeding pests like *N. nipae*, which thrive in sugar-rich tissues.

The SM colonisation followed a similar age-related trend. Infestation severity increased from a mean of 2.38 in Location 1 to 5.31 in Location 2, with the highest levels recorded in the mature blocks, which reached 12.16 and 13.63 in Locations 3 and 4, as shown in Table 3. Tukey's HSD test confirmed that fungal colonisation was significantly greater in older palms at the level of

TABLE 3. COMPARATIVE ANALYSIS OF MEALYBUG (MB) INFESTATION IN TREES ACROSS FOUR GROWTH STAGES AND GEOGRAPHIC LOCATIONS

Location	Total number of trees (N)	Total number of observed canopy levels	MB		SM	
			Mean	Standard error (SE)	Mean	Standard error (SE)
1	30	90	4.16a	0.52	2.38a	0.37
2	30	90	6.33b	0.70	5.31b	0.67
3	30	90	12.46c	0.51	12.16c	0.55
4	30	90	13.73c	0.37	13.63c	0.38

Note: Different letters indicate significant differences in infestation levels among locations ($P < 0.05$). Tukey's HSD (Tukey b) test identified significant pairwise differences between locations at $P < 0.05$. The study sites included Location 1: FGV PM Sahabat 43 North (trees aged 1–3 years), Location 2: FGV PM Sahabat 33 East (4–6 years), Location 3: FGV PM Sahabat 9 West (13 years) and Location 4: FGV PM Sahabat 11 (13 years).

$p < 0.05$. This pattern aligns with the ecological linkage between MB and SM because honeydew produced by MB serves as the substrate for fungal growth. Mature palms, which develop denser canopies and more humid microclimates, provide favourable conditions for both MB activity and subsequent fungal proliferation. Mohd Zin et al. (2023) also reported strong correlations between MB density and SM severity, particularly in older palms, supporting the age-related pattern observed in this study.

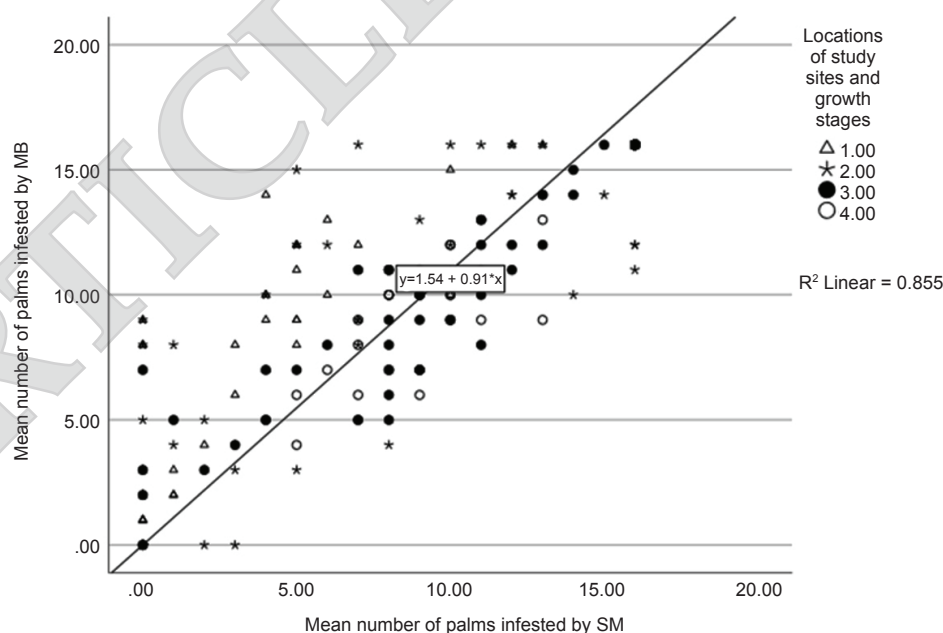
Together, these findings suggest that physiological sugar profiles, canopy structure and microclimatic conditions in mature palms create environments highly conducive to both MB colonisation and secondary fungal development. However, because sugar content and nutrient allocation were not measured directly in this study, these mechanisms remain plausible interpretations supported by existing literature rather than conclusions drawn from the present dataset (Douglas, 2006; Lopes et al., 2019; Puspitasari et al., 2023; Zhou et al., 2013). Further research incorporating biochemical profiling and physiological measurements would help clarify the drivers of age-related susceptibility in oil palm.

A strong positive correlation was observed between the total number of oil palm trees infested by MB and those affected by SM across geographic locations and age groups (Figure 2; Pearson's

correlation, $r_p = 0.94$, $N = 120$, $p < 0.001$), indicating a close ecological relationship between MB density and fungal colonisation.

This relationship reflects the dependence of SM on honeydew produced by phloem-feeding MB, which provides the substrate required for fungal growth (Chomnunti et al., 2014). Higher infestation and mould development in the mid- and lower-canopy strata further support this linkage, as these layers tend to accumulate honeydew and retain humidity. This mechanism aligns with previous physiological studies, including Zhou et al. (2013), who documented substantial daily honeydew secretion in *Phenacoccus solenopsis*. Their findings reinforce the biological basis for the strong field-level correlation observed in this study.

From a management perspective, the strong coupling between MB density and SM severity underscores the importance of monitoring mealybug hotspots as an early warning indicator of impending fungal development. Building on these findings, future research incorporating natural enemy surveys, ant-mealybug interactions, microclimatic measurements, long-term infestation dynamics, as well as more advanced analytical approaches such as regression modelling, would further refine integrated management strategies for *N. nipae* and provide deeper ecological insight under plantation conditions.



Note: The triangle symbol represents Location 1: FGV PM Sahabat 43 North (palms aged 1–3 years); the star symbol represents Location 2: FGV PM Sahabat 33 East (palms aged 4–6 years); the black dot represents Location 3: FGV PM Sahabat 9 West (palms aged 13 years); and the white dot represents Location 4: FGV PM Sahabat 11 (palms aged 13 years).

Figure 2. Correlation between total number of oil palm trees infested by mealybug (MB) and sooty mould (SM).

Validation of the Mealybug-Sooty Mould Severity Index (MSI) for Field-Level Surveillance and Decision-Making

The index values for MB and SM showed clear differences in infestation severity across the four plantation blocks in the FGV Sahabat region (Table 4). Location 1 recorded the lowest MSI values (MB = 0.26; SM = 0.16), reflecting predominantly low to moderate infestation with no trees reaching the critical category. Location 2 showed a moderate increase in severity (MB = 0.38; SM = 0.33), with several trees classified as high but none as very high. In contrast, Locations 3 and 4, both consisting of mature palms aged over 7 years, exhibited substantially higher MSI values. Location 3 recorded MSI values of 0.84 for both MB and SM, with more than two-thirds of trees falling into the critical category. Location 4 showed the highest severity, with MSI at 0.99 and SM at 1.00, indicating near-total canopy saturation by both MB and SM.

These MSI patterns clearly demonstrate that infestation severity increases with palm age and that MB and SM intensities rise in parallel across all locations. The close alignment between observed field conditions and the corresponding MB and SM scores indicates that the MSI effectively captures real variation in pest and fungal severity. This consistency across age groups and plantation blocks supports the reliability of the index and its suitability for field surveillance. Similar index-based approaches have

been widely used in plantation pest management, including the Termite Infestation Severity Index (TISI) developed by Sulaiman et al. (2023) and severity-based economic injury level models for *Tirathaba mundella* by Ming et al. (2020). These studies highlight key strengths of severity indices, such as their simplicity, rapid field applicability, and ability to standardise assessments across observers and sites.

Despite these advantages, index-based tools also have recognised limitations. Their reliance on visual scoring can introduce observer bias, particularly when symptoms are subtle or unevenly distributed across the canopy. Severity classes may oversimplify continuous biological variation, and index values may be influenced by environmental conditions such as light, humidity, or frond accessibility (Kogan & Jepson, 2007). Furthermore, indices do not directly quantify physiological drivers such as sugar content or nutrient allocation, which may underlie infestation patterns. For these reasons, severity indices are most effective when used alongside complementary methods, including microclimatic monitoring, natural enemy surveys and biochemical profiling.

Overall, the MSI developed in this study demonstrates strong construct validity and operational relevance. Its ability to capture clear, biologically meaningful gradients across palm age categories and plantation blocks supports its use as a practical decision-support tool for field-based surveillance and for the early detection of escalating MB-SM pressure.

TABLE 4. MEALYBUG-SOOTY MOULD SEVERITY INDEX (MSI)

Location	Infestation threshold (% of fronds infested) (a)	Weightage (b)	Severity of classification (c)	Total no. of trees infested by MB (d)	MB scores (b) x (d)	Total no. of trees infested by SM (e)	SM scores (b) x (e)
1	0	0.000	None	4	0.00	9	0.00
	1–25	0.125	Low	10	1.25	12	1.50
	26–50	0.375	Moderate	14	5.25	9	3.38
	51–75	0.625	High	2	1.25	0	0.00
	> 76	1.000	Critical	0	0.00	0	0.00
	Total			30	7.75	30	4.875
	MSI			0.26		0.16	
2	0	0.000	None	3	0.00	4	0.00
	1–25	0.125	Low	6	0.75	9	1.13
	26–50	0.375	Moderate	10	3.75	7	2.63
	51–75	0.625	High	11	6.88	10	6.25
	> 76	1.000	Critical	0	0.00	0	0.00
	Total			30	11.375	30	10
	MSI			0.38		0.33	

TABLE 4. MEALYBUG AND SOOTY MOULD SEVERITY INDEX (MSI) (continued)

Location	Infestation threshold (% of fronds infested) (a)	Weightage (b)	Severity of classification (c)	Total no. of trees infested by MB (d)	MB scores (b) x (d)	Total no. of trees infested by SM (e)	SM scores (b) x (e)
3	0	0.000	None	0	0.00	0	0.00
	1–25	0.125	Low	1	0.13	1	0.13
	26–50	0.375	Moderate	4	1.50	1	0.38
	51–75	0.625	High	4	2.50	9	5.63
	> 76	1.000	Critical	21	21.00	19	19.00
	Total			30	25.125	30	25.125
	MSI			0.84		0.84	
4	0	0.000	None	0	0.00	0	0.00
	1–25	0.125	Low	0	0.00	0	0.00
	26–50	0.375	Moderate	0	0.00	0	0.00
	51–75	0.625	High	1	0.63	0	0.00
	> 76	1.000	Critical	29	29.00	30	30.00
	Total			30	29.625	30	30
	MSI			0.99		1.00	

Note: The study sites included Location 1: FGV PM Sahabat 43 North (trees aged 1–3 years), Location 2: FGV PM Sahabat 33 East (4–6 years), Location 3: FGV PM Sahabat 9 West (13 years) and Location 4: FGV PM Sahabat 11 (13 years); MB - mealybug; SM - sooty mould.

CONCLUSION

This study proposed a field-validated MSI that reliably captures variation in infestation severity across palm age classes and canopy strata. The MSI reflects clear biological patterns linking mealybug abundance with secondary sooty mould development, demonstrating strong construct validity under operational field conditions. As a simple, standardised, and sensitive tool, the MSI enhances routine surveillance and supports earlier detection of escalating pest-fungal pressure. Its application strengthens both ecological understanding and practical decision-making within integrated pest management programmes in oil palm plantations.

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