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PiCUS Sonic Tomograph: A Case Study of Crimson Bottlebrush Tree (*Melaleuca citrina* (Curtis) Dum.Cours)

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ABSTRACT

Trees with a decreasing level of health and structure can become a threat to life and property if they are not properly managed. Thus, a regular visual tree assessment (VTA) is essential to monitor the trees' conditions. A recent assessment, July 2022, by VTA on an existing *Melaleuca citrina* in the Forest Research Institute Malaysia (FRIM) showed poor canopy growth colonised by parasitic plants with the emergence of fruiting bodies (conk or mushroom) on its trunk, indicating internal wood decay. Tree inspection using an advanced approach of PiCUS Sonic Tomograph (PiCUS) was performed to evaluate the severity of the decayed trunk. As a non-invasive method, PiCUS measures the wood deterioration in trees using sound wave velocity that moves through the density of the wood. The thicknesses of the residual wall of trees with internal defects were recorded as colour-coded tomograms. The results were then compared with previous observations in the year 2017. The soil penetration test, pH and "The Jar Test" were also adopted to analyse soil properties and condition around the tree. The tomogram images showed an increased percentage of decay from 2017 to 2022 of approximately 2 to 78%, respectively. The sound wood also decreased from 82 to 14% for the respective period. The soil is categorised as silt loamy with pH value of 5.6 to 6.4 while the soil penetration test exceeds a value of 2.06 MPa, which restricts the root growth. This information is vital for further maintenance of urban trees and very useful for managerial decisions.

Keyword: Arboriculture, hazardous tree, internal wood decay, urban tree, visual tree assessment.

INTRODUCTION

Urban trees play an important role in increasing aesthetic values and providing ecological, sociological, and physiological benefits. Research has shown that trees increase property values. Properties surrounded by trees had greater values than those of comparable houses without trees (Des Rosiers et al., 2002; Nowak et al., 2006). The property values increase by 5 to 20% if they are surrounded by green areas (Deepak, 1999). However, trees with a decreasing level of health and structure can threaten life and property if they are not properly managed.

In general, tree health can be initially assessed by observing morphological traits such as leaf colour and canopy density. Regular monitoring of urban trees using the visual tree assessment (VTA) technique is essential to confirm the tree's condition, ensuring public safety and avoiding property damage due to tree failures. The VTA identifies signs and symptoms in trees and their surroundings. An advanced assessment using PiCUS Sonic Tomograph (PiCUS) is carried out when serious signs or symptoms are discovered. For instance, an occurrence of conks shows a possibility of internal decay of the infected tree parts. Decay is the process by which microorganisms break down wood into simpler forms to provide nutrients for their survival (Harris et al., 2004). The decay of wood within a tree trunk is often the cause of tree failure

(Lonsdale, 1999; Schwarze et al., 2000; Shaw et al., 2004). The VTA provides surface information about the tree's risk status, while PiCUS provides valuable evidence on the percentage of internal wood damage affected by the microorganisms.

Trees with structurally weakened diseases such as heart and butt rot are more prone to snapping and falling during heavy storms. Hence, foresters, arborists, physiologists, plant pathologists, and ecologists are trying to find a new method to detect, measure and visualise internal decay using a non-invasive method. Argus Electronic GmbH (Rostock, Germany) developed the PiCUS for the non-invasive detection of internal wood decay and cavities in living trees, which measures variation in the speed of sound across the trunk to determine patterns of wood integrity (Gilbert et al., 2016). The PiCUS measures the wood deterioration in trees using sound wave velocity that moves through the wood density. The thickness of the residual wall of trees with internal defects was captured as a colour-coded tomogram.

Therefore, this study aimed to evaluate the specific factors that contribute to the poor vitality and identify the severity of internal wood decay in a landscape species, *Melaleuca citrina* using the VTA form and PiCUS device, before a further decision can be made. Failure to address the compromised tree health may result in a high risk of safety, such as falling branches or tree toppling, endangering people and property. Additionally, the view of the bottlebrush tree with declining health can diminish the visual attractiveness of the surroundings thus reducing the aesthetic value.

MATERIALS AND METHODS

Study Site and Plant Materials

The study was carried out at the Forest Research Institute Malaysia (FRIM) campus (3.2354 °N, 101.6328 °E). FRIM has an average daily temperature of 27 °C, annual rainfall of 2500 mm, and approximately 76% humidity. Three *M. citrina* (Myrtaceae) trees approximately 30 years old and grown near a building and car parking area were evaluated. *M. citrina* is known as the Crimson Bottlebrush, evergreen shrub to medium size tree from the Myrtaceae family with mature height that can reach 7 to 8 m tall. The trunk has brownish grey bark, fissured with age and has upright branches. Leaves are alternate, simple, lanceolate to elliptical (7x2 cm), and the texture is smooth and leathery. Distinctive red inflorescences resemble a brush and are red in colour. Fruits are small sessile woody capsules clustered around the stems. Each capsule contains many tiny seeds. *M. citrina* is highly recommended by landscapers for its vibrant flower colour and distinctive shape bottlebrush-shaped flowers. This particular species is native to Australia and has been introduced in Malaysia as a landscape trees. The trees have narrow leaves and release a pleasant lemon-like fragrant when crushed. The numerous flowers which are densely packed on the red spike and attract pollinators such as bees and birds adding both beauty and functional to the surrounding environments. Moreover, the Crimson Bottlebrush tree is known as a species with low maintenance requirements making it suitable for urban landscape trees. The mean height and diameter at the breast height of the trees were 17.4 m and 35.2 cm, respectively.

Soil Penetration Resistance and pH

To assess the soil penetration resistance at the planting site of the *M. citrina*, a hand penetrometer (Dickey-John, Soil Compaction Tester, USA) was employed. This instrument is specifically designed to determine the amount of resistance by a cone (tip of the instrument) as it penetrates the top layer of the soil and further into the soil profile (Ahmad Nazarudin et al., 2014). By measuring the highest recorded value of penetration resistance over a distance, the hand penetrometer provides the information on pressure value and soil depth where the soil compaction initiates. While the soil pH and moisture tester meter (Model Dm-15, Japan) measures the soil acidity and moisture content. The metallic surfaces on the soil pH tester were embedded directly onto the soil and the pH reading and soil moisture measurements were recorded. The study employed a random sampling technique within a one-meter radius around the root collar using a penetrometer and a soil pH tester, with 10 sampling points each. The Jar test methods were conducted to analyse soil texture within the study site.

a b

Figure 1. FRIM location within Peninsular Malaysia (a), and red circle is location of study site at FRIM, Kepong, Selangor (b) (source Google earth pro @ 2022)

VTA and PiCUS

Level 1 visual assessment on tree conditions is continuously implemented, especially for trees grown within public areas such as roadsides and buildings. The assessment is limited in scope and involves observation of trees either from vehicles or on foot along designated paths, streets, or sidewalks, with the purpose of identifying potential risk factors. If any signs of tree damage or decay are detected during the preliminary inspection, a visual tree assessment (VTA) is conducted to provide a more thorough evaluation. Level 2 VTA, is a basic assessment where a more comprehensive assessment is performed by walking around the tree (360º), utilising simple tools such as mallet and probe to evaluate the tree and site conditions. This level requires a closer and detail examination on an individual tree. It involves observing factors such as overall tree health, structural integrity, signs of disease or damage and site-specific consideration. Meanwhile, Level 3 is an advanced method that involves more in-depth assessment. It considers specific factors that can affect the tree risk. The assessment process may require advanced tools such as the air spade, sonic tomograph and resistograph. Additionally, the evaluation of structural stability, root conditions and other contributing factors to tree risk may be necessary. The tree risk assessment form developed by the International Society of Arboriculture with some modifications was used. The existing version of the VTA form has been translated into the local language and revised with simplified terminology focusing on structural defects, signs and symptoms and hazards rating. The aim is to create a concise one-page assessment form that enables rapid tree evaluation within a specific area.

VTA has been performed twice (February 2017 and July 2022) for three *M. citrina* (T1, T2 and T3). The VTA assessment covers tree characteristics and health (canopy form, foliage colour and density, and root condition), tree hazard status (poor taper, co-dominant stems, canker and wound), site condition (topography, slope and soil compaction), and target (building, car park, pedestrian and other structures). VTA results can be used to identify the hazard rating and the required monitoring frequency for each tree.

The crown condition of *M. citrina* was viewed aerially using a drone (DJI Phantom 4, China) and PiCUS assessment was performed on the trunk at 35 cm and 70 cm (where conks were observed) from the trunk basal following the manufacturer's instruction (Argus Electronic GmbH) (Figure 2).

The non-invasive techniques such as PiCUS are the best to detect internal decay. The PiCUS is minimally invasive; it provides an image across the entire cross-section, unlike other decay detection methods that require drilling through the bark into the xylem (Smiley and Fraedrich, 1992; Gilbert and Smiley, 2004). Sonic or ultrasonic tomography offers a good balance between accuracy, invasiveness, and ease of use, but at a high cost (Johnstone et al., 2010).

a b c

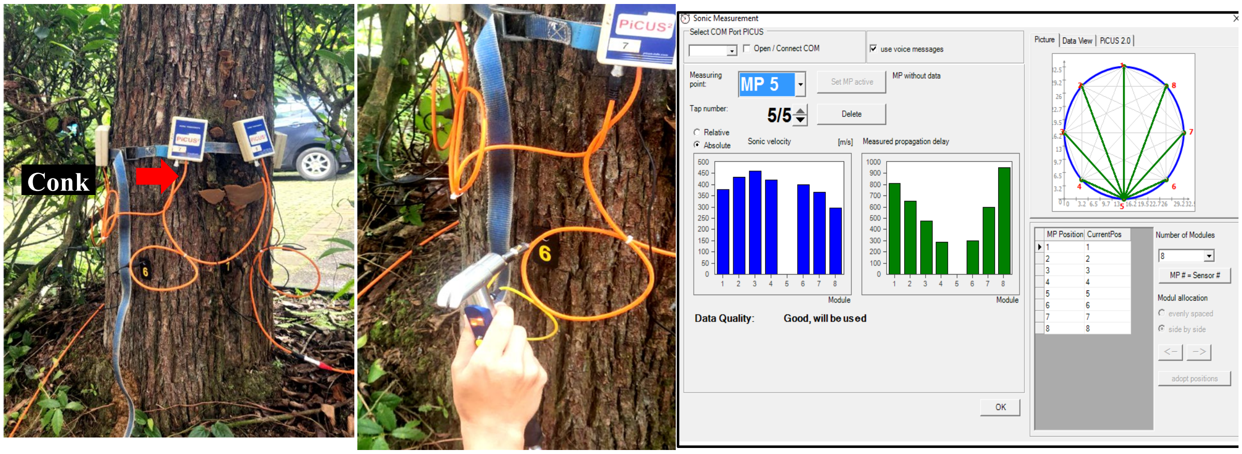

Figure 2. Mounting the sensors on the tree trunk (a), sonic measurement around the trees by tapping an electronic hammer on the nails attached to each sensor (b), and data shown on laptop (c)

Tomogram and Interpretation

The current PiCUS tomogram result at 70 cm level from the ground was compared with the previous tomogram taken in 2017 at a similar height to interpret the spread of decay parts. Applying the current tomogram findings to the 35 cm level, a 3D geometry-image of the internal trunk decay pointing downward to the base of the trunk was then generated to evaluate the severity of the defect.

RESULTS AND DISCUSSION

Visual Tree Assessment

The second assessment in July 2022 found that one of the three *C. citrinus*, the T2 tree, needed a more detailed inspection using PiCUS equipment. The VTA and aerial inspection assessments revealed that the health and structure of T2 decreased and could be risky (Table 1). The health of T2 tree was severe with the emergence of a parasitic mushroom or conk, *Phellinus* sp., on the lower part of the trunk (40 cm level from the ground) (Figure 3a). The presence of conks can be associated with decaying parts of the tree. In addition, twig dieback, dead branches and imbalance canopy form were also observed (Figures 3b and 3c). The bottlebrush trees in the given area have been planted with an approximate distance 3 m between each other. The rooting space for these trees is confined to a narrow area of 1.5 m between a building and a car park lot. Over the years, as the bottlebrush has increased in diameter, the available space for their root system has become limited to approximately 0.6 to 0.7 m (Figures 3d).

Table 1. VTA analysis on the three *M. citrina* trees

VTA characteristics	Year 2017			Year 2022		
	T1	T2	T3	T1	T2	T3
a) Tree appearance						
i. Canopy form	Uneven	Uneven	Uneven	Uneven	Uneven	Uneven
ii. Tree form	Poor	Moderate	Moderate	Moderate	Moderate	Moderate
b) Tree health						
Vigour class	Poor	Poor	Poor	Poor	Poor	Poor
c) Hazard status						
i. Tree damage	Co-dominant, dead branches, stub, epiphyte and vine	Dead branches, stub, conk, epiphyte and vine	Dead branches, stub, epiphyte and vine	Co-dominant, dead branches, stub, epiphyte and vine	Dead branches, stub, epiphyte and vine, twig dieback, high volume of conk at the base of the trunk	Dead branches, stub, twigs dieback, epiphyte and vine
ii. Target under the tree (Usage frequency)	High	High	High	High	High	High
iii. Occupancy (Usage frequency)	High	High	Moderate	High	High	Moderate
iv. Target (removable)	No	No	No	No	No	No
v. Suggested Monitoring cycle						
• Low (12 month)						
• Moderate (6 month)	✓	✓	✓	✓		✓
• High (3 month)					✓	
Hazard rating	**	***	**	**	****	***

Hazard rating	Attributes
**** Severe	Uneven canopy, moderate tree form, poor tree vigour, dead branches, stub, epiphyte, vine, twig dieback, **high volume of conk at the base of the trunk**, high occupancy, target is not removable, tree monitoring cycle high (3 month)
*** High	Uneven canopy, moderate tree form, poor tree vigour, dead branches, stub, conk, epiphyte, vine, **twig dieback**, high occupancy, target is not removable, tree monitoring cycle high (6 month)
** Moderate	Uneven canopy, poor to moderate tree form, poor tree vigour, dead branches, stub, epiphyte, vine, high occupancy, target is not removable, tree monitoring cycle high (6 month)
* Low	Balance canopy, good tree form, good tree vigour, epiphyte and vine, no stub, small quantity of dead branches, no conk, low occupancy, target is removable, tree monitoring cycle low (12 month)

Previous visual assessment indicated that fruiting bodies (conk/mushroom) on *Tilia* spp. were a common indicator of internal decay and a reliable indicator of strength loss threshold (Terho, 2009). Kennard et al. (1996) reported that fruiting bodies, wounds, cankers and fissures indicate tree health decline. An evaluation on 352 historical trees in Hong Kong found defect-disorder significantly increased tree hazard rating and failure potential (Jim and Zhang, 2013). By understanding the factors that drive the failure of the tree, it may be possible to enhance the accuracy of hazard tree risk assessments using VTA in urban areas. This could help decision-makers in allocating resources and implementing best management practices using arboriculture knowledge for a safer environment in the long run.

Observation on *M. citrina* from Year 2017-2022

The VTA assessment revealed that the trees were subject to an unfavourable environment, which may have contributed to their declining health. Specifically, the trees were grown in a limited space for rooting, compacted soil and planted close to buildings and other structures. The trees exhibited signs of poor health, including dead branches, twig dieback, fruiting body emergence, poor canopy density and poor tapered form. Decay at the root or trunk interface and repeated improper pruning practices in the early stages of the trees' lives may have contributed to trunk decay occurrences (Qi et al., 2013).

Epiphytes such as *Pyrossia piloselloides* and *Asplenium nidus*, as well as climbers like *Piper* sp., were observed on all *M. citrina* trunks and branches. While these organisms are not harmful to the host, long-term attachment may lead to complications. The accumulation of organic debris in the vine-epiphyte community contributes to the overall mass of the community, as well as the water inside the debris. Epiphyte biomass can increase photosynthetic biomass by 40 to 150% and can store up to 300 L of water per emergent tree (Diaz et al., 2010). The accumulation of water and debris, along with high humidity, enhances the likelihood of unwanted borers or insects and pathogens on the tree trunk. These factors indicate a risk of failure in the future. All trees were classified as having hazard ratings ranging from moderate to high or severe. T2 was rated as having severe hazard due to its many unfavourable characteristics, as outlined in Table 1, and requires monitoring every 3 months to ensure safety.

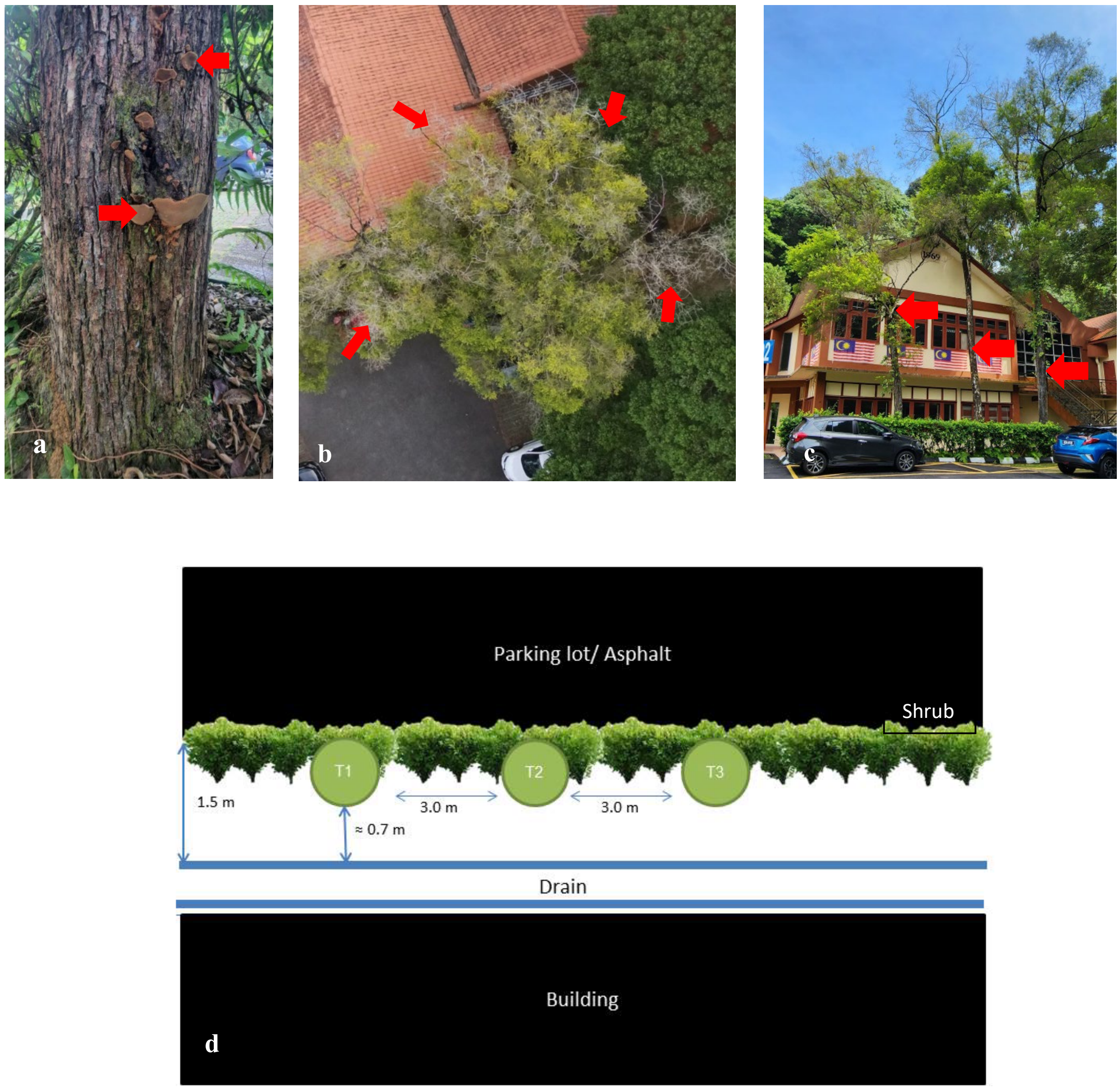

Figure 3. Fruiting bodies inhabitant on the outer part of the trunk (a), twig dieback and dead branches on tree crown (b), *M. citrina* stands and uneven tree forms (c) and site condition illustrations of the planted *M. citrina* (d)

Soil Penetration and pH

The assessment of the soil site conditions revealed the initiation of soil compaction within a depth range of 8 to 20 cm from the top layer of the soil, with the exceeding value of 2.06 MPa. Hasegawa (2008) suggested soil compaction affect roots growth development within the range of 1 to 1.7 MPa, whereas the values of 3 to 4 MPa prohibit it. Sinnett et al. (2008) also indicated that root development and expansion were considerably impeded with the values of 2 to 3 MPa. According to the findings, the compaction restricts normal root growth of the bottlebrush trees. When the root growth is restricted, the mineral or nutrient uptake is reduced. Shaheb et al. (2021) reported a reduction in plant nutrient uptake and growth due to soil compaction which altered plant root architecture and anchorage.

Additionally, the soil tester indicated acidic soil conditions with a pH value of 5.6 to 6.4. By conducting soil texture analysis using "The Jar Test" method, it was determined that the soil consists of approximately 29.31% sand, 44.83% silt and 25.86% clay. The soil can be classified as silt loam and it is generally considered to be fertile with the characteristics of moderate water holding capacity and good drainage with a consideration of organic matter content and nutrient level. Generally, the silt loam soil can be used to plant various types of plant species. However, the specific tree species and their pH preferences should be taken into account when planting trees for optimal growth and development.

Often the true failure of the trees in urban landscape are caused by abiotic disorders, the non-living agents such as, soil, weather changes, wind patterns and temperature. Other external factors (biotic), such as trunk orientation abnormalities, pests and diseases, may also contribute to its potential failure. The accumulation of various stresses related to the study site may contribute to what is known as a "mortality spiral", ultimately leading to the eventual demise and structure failure of the *M. citrina* trees. Schütt et al. (2022) reported that as urban trees continue to grow, their root development is constrained within the limited volume of urban soil. This results in a densely rooted planting space. Consequently, the available water within confined space can quickly diminish due to the escalating water demands of mature trees. The interactions between tree species and soil type have an impact in physiological responses, suggesting that different tree species may not consistently respond to urban soil conditions. Therefore, matching native tree species with the appropriate soil type could be beneficial in optimising the establishment and growth of urban forest projects (Fini et al., 2022).

Wood Strength Loss and PiCUS Sonic Tomograph

Further investigations using the PiCUS on T2 tree revealed an elevated percentage of wood decay from 2017 to 2022, rising from 2 to 78%, respectively (Figure 3). The sound wood at 70 cm level decreased from 82 to 14% in 5 years. Given the alarming estimate of a 68% decline in sound wood on T2, it is imperative for management to carefully consider all relevant factors when determining the removal of a tree, particularly the loss of wood strength over time. According to the strength loss formula by Wagener (1963), conifers can tolerate up to a 33% reduction in strength without posing a danger. Nevertheless, Wagener's approach only applied to conifers lacking additional flaws such as cracks, cankers, or a lean. The examination of over 800 broken and standing trees by Mattheck and Breloer (1998) from temperate regions suggested that having less than 40% of sound wood remaining can increase the risk of a tree trunk breaking unexpectedly. Trees with less than 30% sound wood were most likely to fail, while in the study no trees having 30% sound wood failed. However, some trees still stood with only 30% sound wood, and died unexpectedly with only one or a few branches, reducing the tree stem load and allowing it to stand.

Ciftci et al. (2014) used bending theory to estimate moment capacity loss to define wood strength loss for selected oak trees. Ciftci noted that Wagener's formula had limitations since stem cross-sections and decay areas were not always precisely round, and the formula required bark thickness evaluation. Mattheck and Breloer (1994) observed that Wagener's strength loss model ignores axial forces' tiny size compared to bending stress. Kane and Ryan (2004) suggested that Wagener's formula needed to be more dependable in estimating stem loss. The stem loss formula developed by Wagener (1963) and other researchers like Coder (1989) and Smiley and Fraedrich's (1992) equations were presented based on decay and cross-section having the same centre (Kane et al., 2001; Kane and Ryan, 2004). These findings are specific to softwood to medium hardwood species with decay present in their stems and are relevant to temperate regions. The study noted that the *Maleluca* genus has a wood density similar to conifers, estimated at around 0.689 to 0.802 g/cm^3 by species. However, it should be emphasised that the potential failure of *M. citrina* (T2) in the future cannot be solely attributed to decay defects based on remaining wood thickness only. It should also consider abiotic and biotic stress factors as mentioned earlier. While predicting when a tree will fail is challenging, careful observation and methodical studies can provide valuable insights into the factors that contribute to a tree's collapse (Kane, 2008; Kane and Clouston, 2008).

Given the high potential risks of failure by T2 tree having less than 40% sound wood remaining, it is suggested that management carefully assesses the risks associated with the tree before determining the best course of action. It would minimise the risk of potential harm while still preserving the tree's ecological and aesthetic value. Other alternative strategies such as stacking, pruning or bracing should be carefully considered as they may be necessary, particularly if specific parts of the tree require attention. If the T2 tree must be kept on the ground, these strategies may prove necessary. The presence of standing hazardous trees poses a danger to both public safety and property, with hazard trees being a major cause of litigation in the United States, resulting in more than 200 fatalities annually due to falling trees (Mortimer and Kane, 2004; Schmidlin, 2009). These approaches diminish the likelihood of tree failure while taking a cautious measure and exploring all available options and still prioritising public safety, management costing and environmental conservation.

Figure 3 depicts the progression of wood decay downwards to the trunk base on PiCUS's 3D images. The tomograms showed that the spread of decay within the T2 tree was uneven and that the severity of the damage (78%) poses significant hazards to the surrounding environment. This internal decay has spread horizontally and vertically over time due to the tree's decreased ability to counter the defect. As a consequence, an irregular decay region has developed which is not concentrated at the pith but instead affects the exterior parts of the trunk. The off-centre decayed portion results from the tree's compartmentalisation of the wound during its growth. According to the Compartmentalisation of Decay in Trees (CODIT) concept (Shigo, 1977), decay eventually centres itself in the appropriate locations and stores the decayed or wound inside the trunk as the tree grows. The decayed area only becomes centralised if the compartmentalisation process is effective. However, poor compartmentalisation retains the decaying region near the surface of the trunk. As a result, the tree eventually succumbs to continual stress over an extended period prior to failure (Shigo, 1977, 1979). The non-invasive trunk examination procedure of PiCUS has high efficiency and accuracy. Previous research using PiCUS tomography by Durlak et al. (2017), confirmed the precise location of changes caused by the decay after tree trunk cutting. Given that this research was conducted in a tropical region, any management decisions regarding the removal of trees should consider the risk of failure, costing, threshold for strength loss and wood properties, as the ability of trees to withstand prolonged periods may differ from previous findings. This finding is valuable for management to execute acute solutions in their actions to ensure workplace safety.

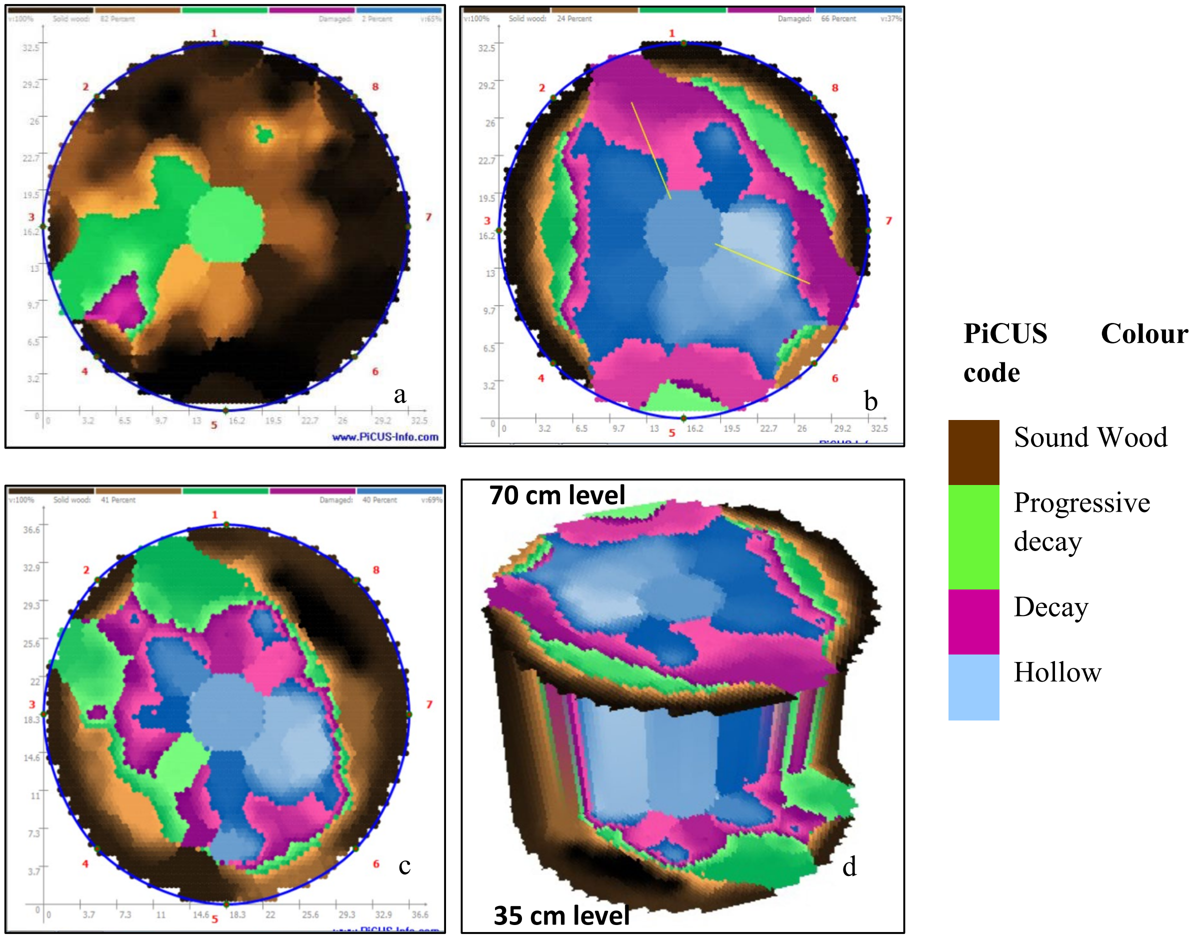

Figure 3. Tomograms of *M. citrina* (T2) tree recorded at 70 cm level in 2017 (a), 70 cm level in 2022 (b), 35 cm level in 2022 (c), and 3D tomogram image of the internal image wood decay recorded at 70 cm and 35 cm level in 2022 (d)

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CONCLUSIONS

Based on the findings, it can be deduced that planting medium-sized trees such as *M. citrina* near small space area between building, poor pruning technique and low tree maintenance would experience cumulative stress over time, resulting in compromised health and potential risks. Best management practice in arboriculture should be implemented and well executed. The VTA played a crucial role in identifying and assessing the signs and symptoms exhibited by the trees, providing valuable information for determining the need for advanced level assessment. Using advanced tools such as PiCUS Sonic Tomograph for detecting the spread of internal decay is a must to ensure that valuable information can be obtained. Trees categorised as having low or moderate potential risk of failure should be subjected to regular monitoring, ideally twice a year. However, trees falling under the severe and high risk categories necessitate immediate action. There are not many best management practices on saving the declining trees that will be effective and are often limited to reversing the tree's conditions. Regular monitoring is necessary for detecting any changes in the health of the tree and addressing potential issues promptly. Additionally, it is vital to consider other contributing factors that may lead to tree failure, including environmental conditions and site specific characteristics. By proactively managing and addressing the health concerns of landscape trees, management can effectively uphold the overall safety and well-being of the surrounding environments. This approach will minimise the risk of failure, mitigate the potential for injuries to the users and prevent the loss of life.

AUTHORS CONTRIBUTION

AHMS, ANMR and RK conceived and designed the analysis. AHMS collected the data and performed the analysis. AHMS, ANMR and RK wrote the paper, and ANMR checked and approved the submission.

ETHICS APPROVAL

This study was conducted on private property, no permission was required, and no plant samples were taken out from the premises.

CONFLICT OF INTEREST

The author(s) declare(s) that they have no competing interests.

FUNDING

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