https://doi.org/10.26525/jtfs2017.29.4.428437

THE USE OF SPECTROSCOPY TO DETERMINE THE PROPERTIES AND EVALUATION OF EXTRUDED TEA LEAF-PLASTIC COMPOSITES

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Submitted March 2016; accepted April 2017

This study determined the color change and the physical properties of extruded tea leaf-plastic composite (TPC) after accelerated weathering. The physical properties in TPC were studied using near infrared (NIR) spectroscopy. TPC experienced both change in color and loss of mechanical properties after weathering. The surface characteristics of TPCs also changed significantly after weathering. Exposure of TPC surfaces to weathering resulted in darkening of the color. The average board density (D), modulus of elasticity (MOE) and the modulus of rupture (MOR), for TPCs without weathering, were significantly larger than those for TPCs with different degrees of weathering. The majority of D, MOE and MOR changes occurred during the first 500 hours. The normalised difference vegetation index (NDVI) for TPC without weathering was significantly higher than samples with different durations of weathering. However, there was no significant difference between the values for different exposure times. The NDVI was the most important factor in determining D or MOE. Both the NDVI and the normalised difference lignin index (NDLI) values were used to predict D, using multiple linear regression. The results showed that NIR spectroscopy could potentially be used to determine the properties of tea leaf-plastic composites.

Keywords: Wood-plastic composite (WPC), weathering, color coordinate, normalised difference vegetation index (NDVI), normalised difference lignin index (NDLI)

INTRODUCTION

Wood-plastic composites (WPC), which use wood flour and polyolefins, are of interest scientifically as well as commercially because WPC combines the best properties of both polyolefins and wood particles (Kallakas et al. 2015). New generation of WPC is an environment-friendly green material, created from the product of forestry and plastic industries (Clemons 2002, Pritchard 2004). This type of new material is manufactured using recycled wood flour and plastic resins.

The WPCs are widely used in outdoor environments. However, weathering is of particular concern because it considerably affects the durability of WPCs. It has been well documented that WPCs exposed to weathering can experience color change, which decreases the aesthetic appeal. There is also loss of mechanical properties which limits their performance (Stark & Matuana 2004, Stark 2007). The color differences and the brightness of WPCs after three months of weathering increase to the maximum value (Kiguchi et al. 2007). The color changes in composites are not a function of the manufacturing process but the resistance to weathering, and the differences are more significant in the first 1000 h (Stark et al. 2004). The density of WPC decreases with weathering. Damage to the surface causes a reduction in density throughout the weathering process (Stark and Matuana 2007). The degradation of plastic is more severe than wood in composite materials (La Mantia and Morreale 2008). Taiwan produces large amounts of tea and a large quantity of waste from the tea industry remains unutilised. There were almost nine thousand tons of tea leaf waste in 2012 (EPA 2012). Therefore, industrial tea leaf waste has been used to produce tea leaf-plastic composites (TPC), and thus the need to understand the performance of weathering in TPC.

For almost two decades near infrared (NIR) spectroscopy has been a commonly used nondestructive technique for wood analysis. The NIR spectroscopy with diffuse reflectance is used to directly and nondestructively examine a large number of samples, thereby saving the time and reagents that are necessary for chemistry-based examinations (Diesel et al. 2014). The NIRs are used for on-line or on-site measurement of various organic materials such as agricultural products, foods, polymers, textiles, pharmaceuticals and petrochemicals (Tsuchikawa and Kobori 2015). The vegetation index (VI) were derived using two or more spectral bands, such as the normalised difference vegetative index (NDVI), the normalised difference nitrogen index (NDNI), the normalised difference lignin index (NDLI) and the cellulose absorption index (CAI). The VI has been used to estimate plant chlorophyll content, water content, oxygen binding and plant nitrogen status (Serbin et al. 2013, Henik 2012, Sims & Gamon 2003, Serrano et al. 2002). Therefore, the objective of this study was to produce extruded TPC and to determine its density, bending strength and color change after accelerated weathering. The study also determined the viability of the use of NIR spectroscopy to estimate density and bending strength in TPC.

MATERIALS AND METHODS

Materials and TPC manufacturing

The recycled leaf flour of green tea was prepared by Uni-President Enterprise Co., Ltd., Taiwan. The green tea leaf flour was filtered using a mesh with a particle size of 125 µm or smaller. The tea flour was initially dried in an oven at 103 ± 3 °C for 24 h, and left in the oven to cool to room temperature. The cooled flour was sealed in aluminum foil bags for TPC manufacturing. Recycled high density polyethylene (HDPE) pellets were used as the matrix component. Maleic anhydride polypropylene was used as the coupling agent and zinc stearate ($Zn(C_{18}H_{35}O_2)_2$, ZnSt) was used as the lubricant. Fine wood flour (< 125 µm) was used to improve the tensile and flexural strength of WPCs and to reduce swelling due to water adsorption, as recommended by Leu et al. (2012).

Tea leaf flour and recycled plastics were mixed at a mass ratio of tea leaf:plastic = 50:50, before compounding and extrusion. Coupling agent and lubricant were added to the tea leaf/plastic mixture to obtain the final TPC product. The material compositions of the coupling agent, lubricant, tea leaf flour and plastic ratios were 3, 3, 47 and 47%, respectively. Leu et al. (2012) suggested that maintaining wood content at 50% or less produced the best mechanical properties, and wood content of more than 50% resulted in a reduction in all physical and mechanical properties of WPCs.

Tea leaf flour and plastic particles were compounded at 180 °C in a mixer for 5 min, using a mixing speed of 55 rpm. Before extrusion, the compounded tea-plastic particles were heated to 103 ± 2 °C for 24 h. The TPC was extruded using a single-screwed extruder. The screw diameter was 7 mm, and the length to diameter ratio was 28:1. During the extrusion, the temperature profiles for the four processing zones were 150, 155, 165 and 170 °C, and the die temperature was 180 °C. The rotational speed of screw was 40 rpm, and the pressure at the die was 4.0 MPa. The extruded TPC was 95 mm wide and 4.5 mm thick. The length of the TPC depended on the extrusion time and speed.

Accelerated weathering test

Quantitative ultraviolet (QUV) accelerated weathering testing is a laboratory simulation of the damaging forces of weather, and is used to predict the relative durability of materials that are exposed to outdoor environments. The QUV testing takes place in an accelerated weathering chamber, which is designed to create a highly flexible mix of UV light, temperature and moisture conditions (Çakicier et al. 2011). In the QUV chamber, the TPC specimens (4.5 mm × 13.5 mm × 130 mm) were exposed to an accelerated weathering procedure. The weathering experiment was performed by cycles of UV-light irradiation for 2 h followed by a water spray for 18 min in an accelerated weathering test cycle chamber. The average irradiance was about 340 nm (UVA 340 lamps) and the temperature in the chamber was approximately 45 °C. A total of 150 samples with 30 replicates were removed for analysis after 0 (control), 500, 1000, 2000 and 3000 h of weathering.

NIR spectroscopy measurement

The NIR reflectance spectra was expressed in the form of log (1/R) and was obtained from the longitudinal section of TPC samples using a spectroradiometer from 350 to 2500 nm, at 1 nm intervals. A fiber optic probe with an 8 mm spot diameter was oriented perpendicular to the surface of the TPC sample. A polytetrafluoroethylene panel was used as the white reference. Fifteen consecutive scans were taken, and averaged to produce a single spectrum. The NDVI, NDLI, NDNI and CAI were derived using R packages (v. 3.0.2, https://www.r-project.org/). NDVI utilises two (subscripts) narrow bands reflective (R) to measure the depth of chlorophyll absorption (Sims and Gamon 2003):

$$NDVI = (R_{800}-R_{680})/(R_{800}+R_{680}) \quad (1)$$

$$NDNI = [\log(1/R_{1510}) - \log(1/R_{1680})]/[\log(1/R_{1510}) + \log(1/R_{1680})]) \quad (2)$$

$$NDLI = [\log(1/R_{1754}) - \log(1/R_{1680})]/[\log(1/R_{1754}) + \log(1/R_{1680})]) \quad (3)$$

NDNI and NDLI are indices that represent nitrogen and lignin in native shrub vegetation (Serrano et al. 2002). CAI utilises three narrow bands to measure the depth of cellulose absorption (Serbin et al. 2013) with a scaling factor of 100:

$$CAI = 100\ [(R_{2030} + R_{2210})/2 - R_{2100}] \quad (4)$$

Color coordinates

Color coordinates were measured using a CM-3600 spectroscopic colorimeter. Illuminant D65 with a 10° observer angle was used and the diameter of the observation window was 8 mm. The samples were placed on the observation windows to measure L* (lightness), a* (redness) and b* (yellowness) based on the Commission Internationale de l'Eclairage (CIE) Lab system that was developed by the International Commission on Illumination (CIE 1976). The changes in the various color parameters over time were evaluated by comparing the results with the initial measurements using the following equations:

$$\Delta L^* = L^*_T - L^*_0 \quad (5)$$

$$\Delta a^* = a^*_T - a^*_0 \quad (6)$$

$$\Delta b^* = b^*_T - b^*_0 \quad (7)$$

$$\Delta E^* = [(\Delta L^*)^2+(\Delta a^*)^2+(\Delta b^*)^2]^{1/2} \quad (8)$$

where ΔE^* represents the overall color difference for the samples. The T and 0 represent the time after weathering and the initial measurements, respectively.

Density and bending strength tests

The density (D) of the TPC was measured after accelerated weathering. To determine the effects of deterioration on TPC, the changes in sample weights and thicknesses were measured after 500, 1000, 2000 and 3000 h of weathering. Mechanical properties were tested using static bending tests. The static bending was performed using UH-10A universal-type testing machine at the School of Forestry and Resource Conservation, National Taiwan University. The parameters and reference standards are summarised below.

Bending tests were performed in accordance with ASTM D790-10 (2010) for the mechanical properties of lumber and wood-base structural material. The tests determined the static modulus of elasticity (MOE) and the modulus of rupture (MOR), calculated using the following equations:

$$MOE = \frac{\Delta P_b}{\Delta y} \cdot \frac{L^3}{4bd^3} \quad (9)$$

$$MOR = \frac{3P_{b\ max}\ L}{2bd^2} \quad (10)$$

where ΔP_b is the difference between the upper and lower limits of the loading of bending (N) in the proportional regions, Δy is the deflection with respect to ΔP_b (mm), L is the span of the two holding points (mm), d is the depth of the specimen (mm), b is the width of the specimen at the cross section (mm) and $P_{b\ max}$ is the maximum loading of bending (N).

Statistical analysis

Statistical analysis used was Analysis of Variance (ANOVA). The differences in experiment results for different test groups were analysed using Tukey test, with 95% confidence intervals. Finally, a linear and multiple regression analysis were performed to establish the relationships between spectral characteristics (NDVI, NDLI, NDNI and CAI) and the flexural properties (D, MOE and MOR).

RESULTS AND DISCUSSION

Visual surface characteristics

The changes in surface morphology of the TPCs were examined using stereo-microscope before and after weathering tests and the results are shown in Figure 1. Before the weathering tests, the surfaces of the TPCs were smooth, but after weathering, different severities of cavities were observed. The surface characteristics of TPCs also changed significantly after weathering. Visual inspection showed that the surface layer was eroded, which created several cavities. The surfaces of weathered TPC had voids because tea-leaf particles were lost during weathering. Surface voiding was probably due to both PE photo-degradation and tea leaf particle swelling or washing, as the composites were unstabilised.

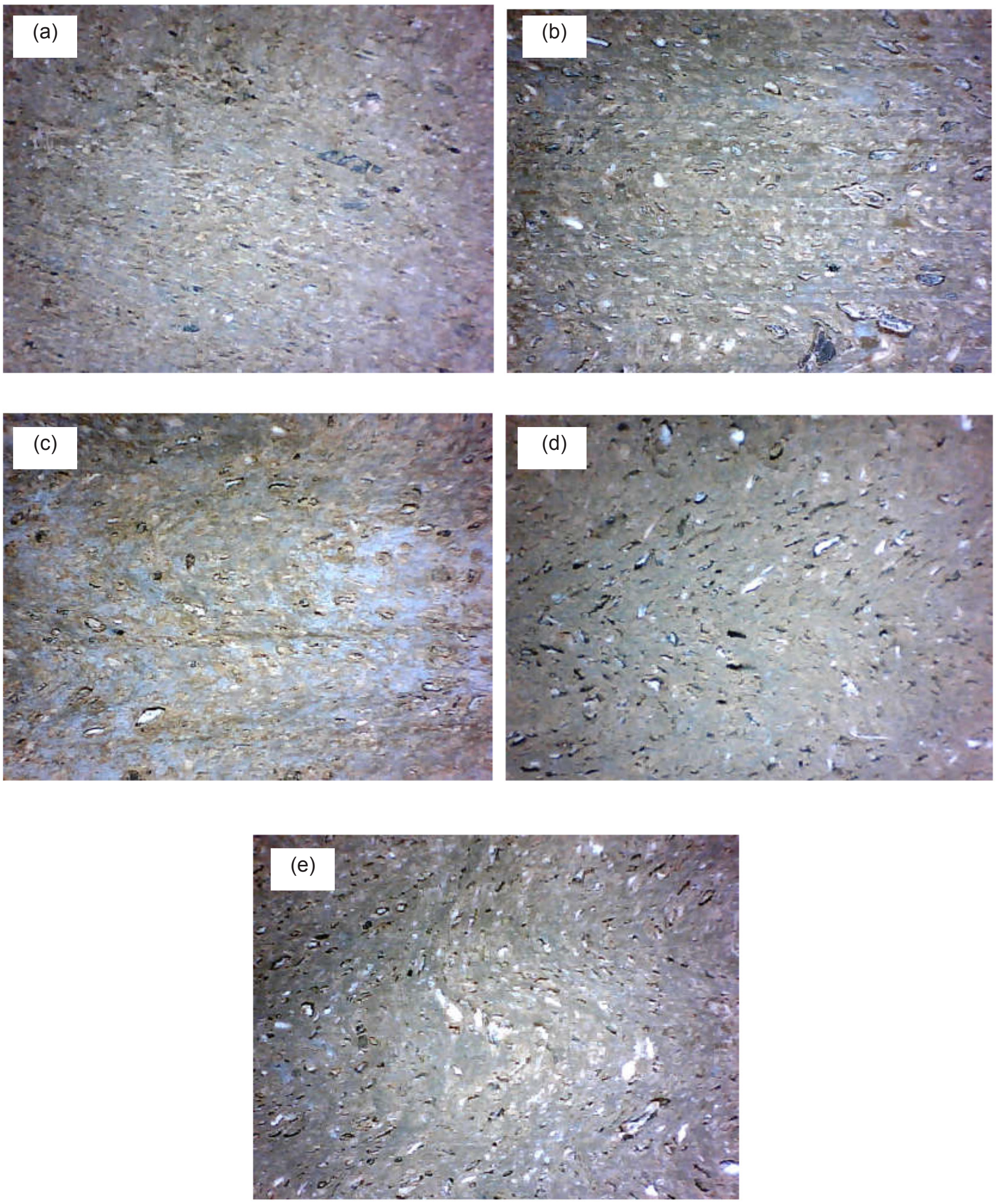

Figure 1 Photographs of extruded tea leaf-plastic composite surfaces (x 40) before weathering (a), and after 500 (b), 1000 (c), 2000 (d) and 3000 h (e) of accelerated weathering by stereo microscope

Many studies have observed cracks on the surface of WPCs during natural or accelerated weathering (Kiguchi et al. 2007, Stark & Matuana 2004, 2007, Yang et al. 2015). Stark and Matuana (2007) proposed that surface degradation of WPCs was a complex combination of degradation of HDPE (high density PE), due to exposure to xenon-arc radiation and changes in wood particles, due to the combination of exposure to xenon-arc radiation and water spray. Yang et al. (2015) reported that while cracking was also observed on the surfaces of WPC, the damage was not deep enough to penetrate the outer layer of the plastic matrix, so the majority of the plastic matrix remains on the surface of WPCs.

Color changes

The changes in ΔL* (lightness), Δa* (redness), Δb* (yellowness) and total color (ΔE*) for TPC surfaces over different periods of exposure are shown in Figure 2. The effect of weathering on ΔL* is shown in Figure 2a. During the first 500 h of weathering, the ΔL* value increased to nearly 1.8 and weathering clearly resulted in lightening of the color. However, the ΔL* value for all composites decreased as exposure time increased from 500 h to 3000 h. After 3000 h of exposure, the ΔL* value decreased significantly. TPC that was not weathered exhibited less lightening of the color.

Figure 2b, 2c and 2d showed that Δa*, Δb* and ΔE* values of TPC surfaces increased as the exposure time increased. The change in the parameters, L*, a* and b* during UV exposure contributed to the change in value ΔE*. The data showed that exposure of TPC surfaces to weathering resulted in darkening. Weathering of TPC changed the material color. The ranges of ΔL* and ΔE* values for TPCs, after weathering, were 0.2–1.8 and 3.0–5.0, respectively. A comparison with changes in ΔL* and ΔE* values for WPC (Lee et al. 2012, Fabiyi et al. 2008) showed that TPC exhibited better lightening and color stability.

Chen et al. (2014) reported that delignification samples were marked by even larger increases in both Δa* and Δb* values. Stark (2006) reported that the exposure to each weathering cycle clearly resulted in composite lighting, and the increase in L* was much less when the samples were exposed to UV light only, which demonstrated

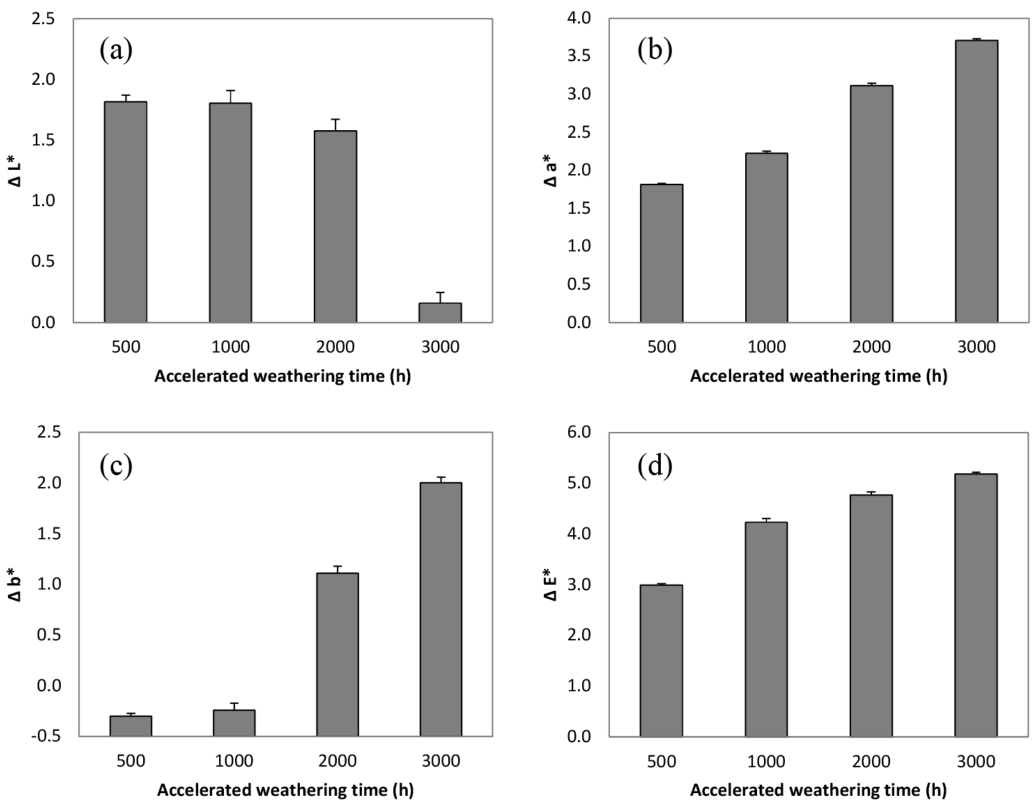

Figure 2 Changes in color parameters of tea leaf-plastic composites as a function of accelerated UV weathering duration (n = 30); ΔL* = lightness, Δa* = redness, Δb* = yellowness and ΔE* = total colour

that water spray has a large effect on color fading. Stark (2007) noted that the color of WPCs primarily reflected the color and color change in wood during weathering, and water exposure may contribute to discoloration through physical mechanisms. Washing the surface removes some of the extractives that impart color, and main components, which is probably the main reason for color fading (Stark 2006, 2007). Yang et al. (2015) reported that the color difference significantly increased in lightness in the first 90 days of weathering exposure, but notable cracking and mass loss in components occurred after 90–180 days.

Flexural properties

The differences in the average air-dried D, MOE and MOR for TPCs for different periods of accelerated weathering was analysed using ANOVA. There were significant differences in flexural properties for different periods of exposure. A comparison of the average flexural properties for TPCs is shown in Table 1. According to the Tukey test results, the average values for D and MOR for TPCs without weathering were significantly larger than those for TPCs with different periods of weathering (500 – 3000 h). However, there were no statistically significant differences between the different exposure durations. UV radiation and water spray reduced the D, MOE and MOR values, and the impact strength increased, as TPC material properties were weaker than the control group. In this study, the degradation rates for flexural properties in TPC were lower than the previously reported values for WPC. By referring to a comparison with the changes for MOE, MOR and WPC (Lee et al. 2012, Yang et al. 2015), TPC had lower strength properties.

Table 1 shows that the flexural properties of all composites generally decreased as the weathering duration increased. The majority of the flexural D, MOE and MOR changes occurred during the first 500 h. This result was similar to that reported by Stark et al. (2004) and Lee et al. (2012), who investigated the loss in MOE and MOR for WPC after weathering.

Lee et al. (2012) noted that polystyrene (PS)-based WPCs exhibited the most severe degradation because there was photo-oxidation on the surface, and the degradation of PE-based WPCs was the mildest. These results were consistent with the changes in the surface cracking and flexural properties of the composites. Stark (2007) noted that exposing the WPCs to UV light only resulted in a small decrease in MOE for the extruded composites with no significant change in strength, and exposure to moisture adversely affected the mechanical properties. The loss in strength was probably due to moisture penetration into the WPC which degraded the wood-polymer interface. The degradation rates of flexural properties in TPC were lower than WPC after the weathering test, and it may be caused by the different composition between tea and wood fibers (Stark et al. 2004).

Vegetation indices

The four indices, NDVI, NDLI, NDNI and CAI were derived using spectroscopy. Henik (2012) noted that the NDVI is used to evaluate plant nitrogen status, chlorophyll content, green

Table 1 Average air-dried density (D, g cm^{-3}), modulus of elasticity (MOE, GPa), modulus of rupture (MOR, MPa), and moisture content (MC, %) of tea leaf-plastic composites after accelerated weathering for different treatment durations

Treatment duration	n	D	MOR	MOE	MC
0 h	30	1.17 (0.02)^{c}	19.3 (2.51)^{b}	1.8 (0.11)^{a}	1.25 (0.48)^{ab}
500 h	30	1.15 (0.01)^{b}	16.8 (2.35)^{a}	1.6 (0.13)^{a}	1.20 (0.21)^{a}
1000 h	30	1.14 (0.01)^{ab}	17.2 (2.91)^{ab}	1.6 (0.13)^{a}	1.24 (0.27)^{ab}
2000 h	30	1.14 (0.00)^{a}	17.3 (3.17)^{a}	1.6 (0.12)^{a}	1.37 (0.34)^{b}
3000 h	30	1.14 (0.01)^{ab}	17.1 (2.52)^{ab}	1.5 (0.11)^{a}	2.03 (0.44)^{c}

Numbers in the parentheses indicate standard deviation (SD); different letters (a, b and c) in the column indicate a significant difference at the 0.05 level by ANOVA and Turkey's test.

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INTRODUCTION

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Statistical analysis

Statistical analysis used was Analysis of Variance (ANOVA). The differences in experiment results for different test groups were analysed using Tukey test, with 95% confidence intervals. Finally, a linear and multiple regression analysis were performed to establish the relationships between spectral characteristics (NDVI, NDLI, NDNI and CAI) and the flexural properties (D, MOE and MOR).

RESULTS AND DISCUSSION

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The changes in surface morphology of the TPCs were examined using stereo-microscope before and after weathering tests and the results are shown in Figure 1. Before the weathering tests, the surfaces of the TPCs were smooth, but after weathering, different severities of cavities were observed. The surface characteristics of TPCs also changed significantly after weathering. Visual inspection showed that the surface layer was eroded, which created several cavities. The surfaces of weathered TPC had voids because tea-leaf particles were lost during weathering. Surface voiding was probably due to both PE photo-degradation and tea leaf particle swelling or washing, as the composites were unstabilised.

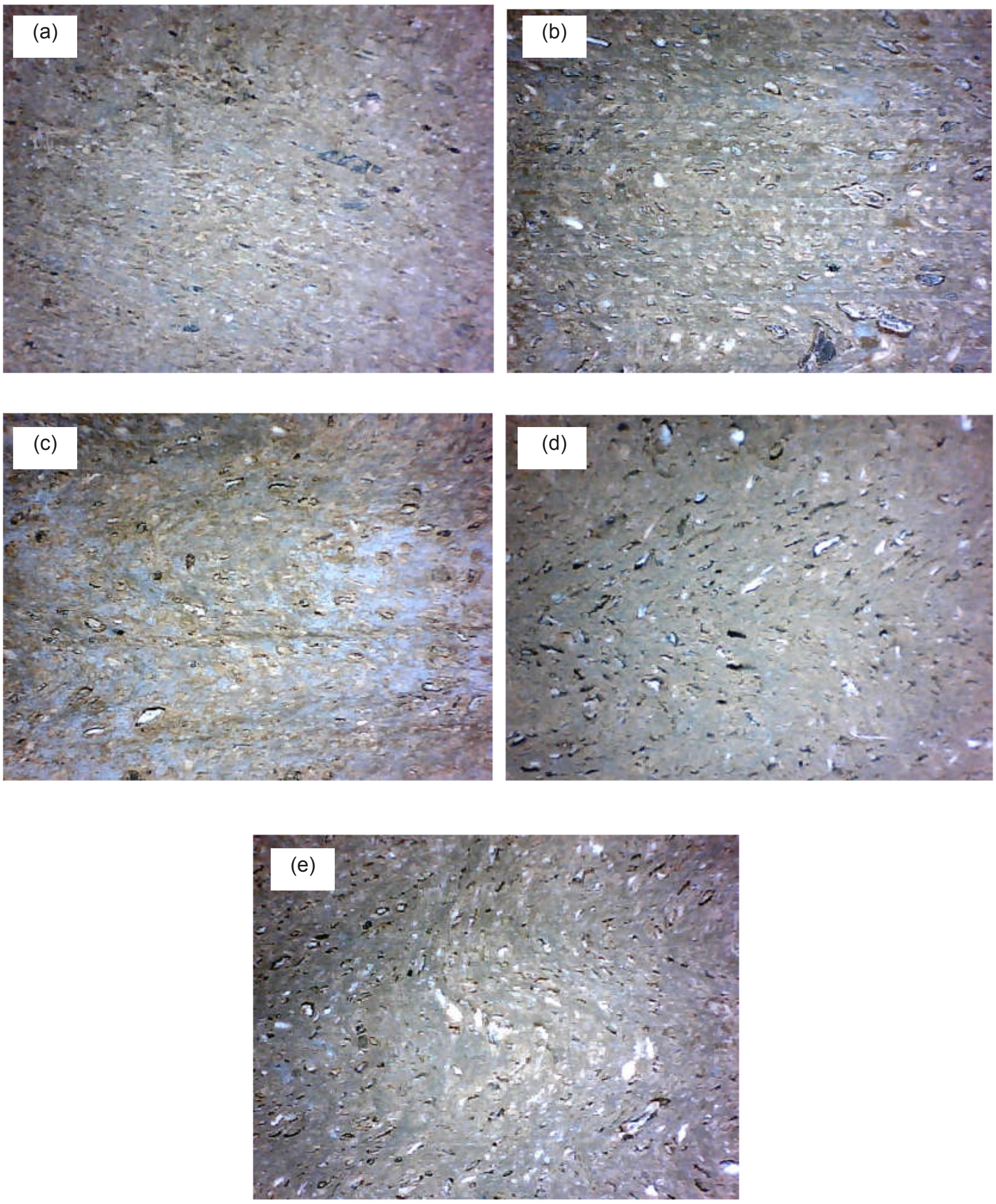

Figure 1 Photographs of extruded tea leaf-plastic composite surfaces (x 40) before weathering (a), and after 500 (b), 1000 (c), 2000 (d) and 3000 h (e) of accelerated weathering by stereo microscope

Many studies have observed cracks on the surface of WPCs during natural or accelerated weathering (Kiguchi et al. 2007, Stark & Matuana 2004, 2007, Yang et al. 2015). Stark and Matuana (2007) proposed that surface degradation of WPCs was a complex combination of degradation of HDPE (high density PE), due to exposure to xenon-arc radiation and changes in wood particles, due to the combination of exposure to xenon-arc radiation and water spray. Yang et al. (2015) reported that while cracking was also observed on the surfaces of WPC, the damage was not deep enough to penetrate the outer layer of the plastic matrix, so the majority of the plastic matrix remains on the surface of WPCs.

Color changes

The changes in ΔL* (lightness), Δa* (redness), Δb* (yellowness) and total color (ΔE*) for TPC surfaces over different periods of exposure are shown in Figure 2. The effect of weathering on ΔL* is shown in Figure 2a. During the first 500 h of weathering, the ΔL* value increased to nearly 1.8 and weathering clearly resulted in lightening of the color. However, the ΔL* value for all composites decreased as exposure time increased from 500 h to 3000 h. After 3000 h of exposure, the ΔL* value decreased significantly. TPC that was not weathered exhibited less lightening of the color.

Figure 2b, 2c and 2d showed that Δa*, Δb* and ΔE* values of TPC surfaces increased as the exposure time increased. The change in the parameters, L*, a* and b* during UV exposure contributed to the change in value ΔE*. The data showed that exposure of TPC surfaces to weathering resulted in darkening. Weathering of TPC changed the material color. The ranges of ΔL* and ΔE* values for TPCs, after weathering, were 0.2–1.8 and 3.0–5.0, respectively. A comparison with changes in ΔL* and ΔE* values for WPC (Lee et al. 2012, Fabiyi et al. 2008) showed that TPC exhibited better lightening and color stability.

Chen et al. (2014) reported that delignification samples were marked by even larger increases in both Δa* and Δb* values. Stark (2006) reported that the exposure to each weathering cycle clearly resulted in composite lighting, and the increase in L* was much less when the samples were exposed to UV light only, which demonstrated

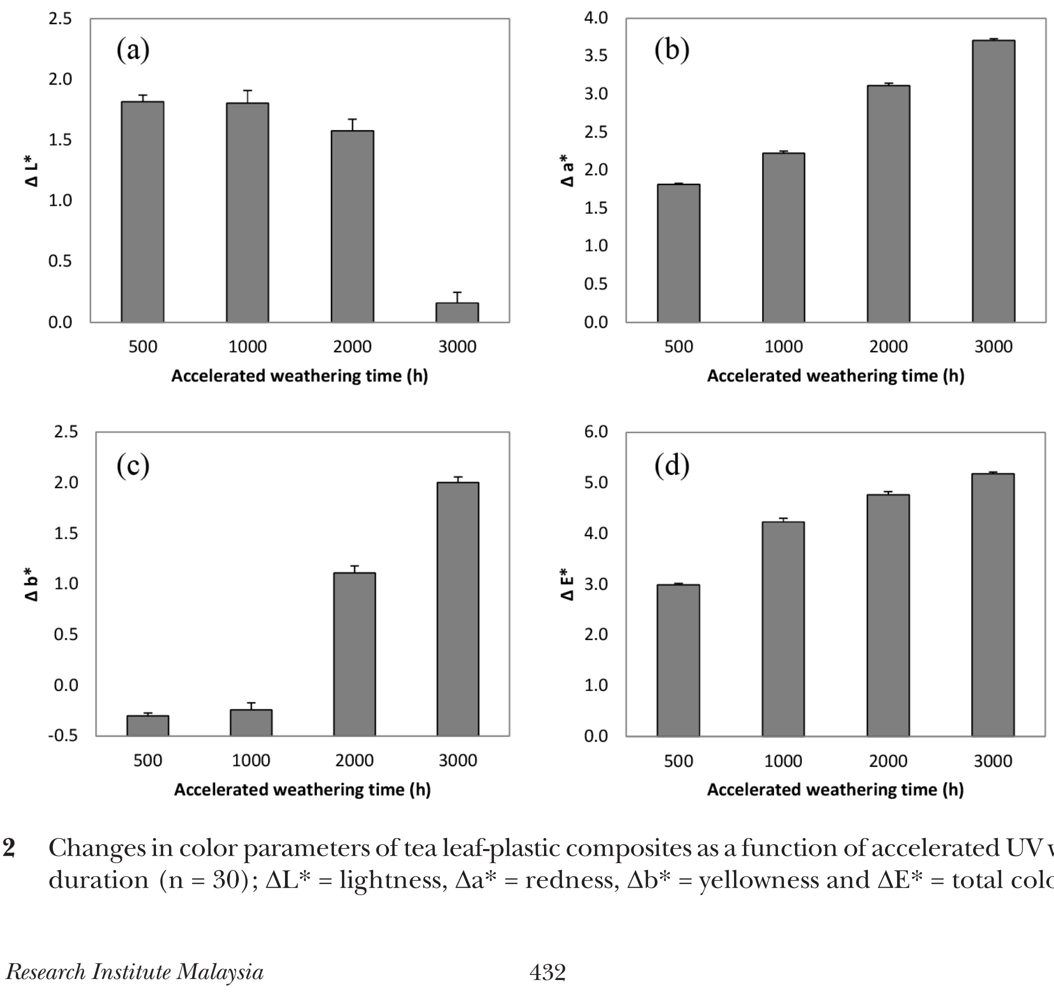

Figure 2 Changes in color parameters of tea leaf-plastic composites as a function of accelerated UV weathering duration (n = 30); ΔL* = lightness, Δa* = redness, Δb* = yellowness and ΔE* = total colour

that water spray has a large effect on color fading. Stark (2007) noted that the color of WPCs primarily reflected the color and color change in wood during weathering, and water exposure may contribute to discoloration through physical mechanisms. Washing the surface removes some of the extractives that impart color, and main components, which is probably the main reason for color fading (Stark 2006, 2007). Yang et al. (2015) reported that the color difference significantly increased in lightness in the first 90 days of weathering exposure, but notable cracking and mass loss in components occurred after 90–180 days.

Flexural properties

The differences in the average air-dried D, MOE and MOR for TPCs for different periods of accelerated weathering was analysed using ANOVA. There were significant differences in flexural properties for different periods of exposure. A comparison of the average flexural properties for TPCs is shown in Table 1. According to the Tukey test results, the average values for D and MOR for TPCs without weathering were significantly larger than those for TPCs with different periods of weathering (500 – 3000 h). However, there were no statistically significant differences between the different exposure durations. UV radiation and water spray reduced the D, MOE and MOR values, and the impact strength increased, as TPC material properties were weaker than the control group. In this study, the degradation rates for flexural properties in TPC were lower than the previously reported values for WPC. By referring to a comparison with the changes for MOE, MOR and WPC (Lee et al. 2012, Yang et al. 2015), TPC had lower strength properties.

Table 1 shows that the flexural properties of all composites generally decreased as the weathering duration increased. The majority of the flexural D, MOE and MOR changes occurred during the first 500 h. This result was similar to that reported by Stark et al. (2004) and Lee et al. (2012), who investigated the loss in MOE and MOR for WPC after weathering.

Lee et al. (2012) noted that polystyrene (PS)-based WPCs exhibited the most severe degradation because there was photo-oxidation on the surface, and the degradation of PE-based WPCs was the mildest. These results were consistent with the changes in the surface cracking and flexural properties of the composites. Stark (2007) noted that exposing the WPCs to UV light only resulted in a small decrease in MOE for the extruded composites with no significant change in strength, and exposure to moisture adversely affected the mechanical properties. The loss in strength was probably due to moisture penetration into the WPC which degraded the wood-polymer interface. The degradation rates of flexural properties in TPC were lower than WPC after the weathering test, and it may be caused by the different composition between tea and wood fibers (Stark et al. 2004).

Vegetation indices

The four indices, NDVI, NDLI, NDNI and CAI were derived using spectroscopy. Henik (2012) noted that the NDVI is used to evaluate plant nitrogen status, chlorophyll content, green

Table 1 Average air-dried density (D, g cm^{-3}), modulus of elasticity (MOE, GPa), modulus of rupture (MOR, MPa), and moisture content (MC, %) of tea leaf-plastic composites after accelerated weathering for different treatment durations

Treatment duration	n	D	MOR	MOE	MC
0 h	30	1.17 (0.02)^{c}	19.3 (2.51)^{b}	1.8 (0.11)^{a}	1.25 (0.48)^{ab}
500 h	30	1.15 (0.01)^{b}	16.8 (2.35)^{a}	1.6 (0.13)^{a}	1.20 (0.21)^{a}
1000 h	30	1.14 (0.01)^{ab}	17.2 (2.91)^{ab}	1.6 (0.13)^{a}	1.24 (0.27)^{ab}
2000 h	30	1.14 (0.00)^{a}	17.3 (3.17)^{a}	1.6 (0.12)^{a}	1.37 (0.34)^{b}
3000 h	30	1.14 (0.01)^{ab}	17.1 (2.52)^{ab}	1.5 (0.11)^{a}	2.03 (0.44)^{c}

Numbers in the parentheses indicate standard deviation (SD); different letters (a, b and c) in the column indicate a significant difference at the 0.05 level by ANOVA and Turkey's test.

leaf biomass and grain yield. The NDVI has a significant effect on the caffeine content, followed by epicatechin and epigallocatechin, and has some effect on other chemical parameters (Dutta 2013). Serrano et al. (2002) reported that the NDNI is significantly correlated to foliar N concentration and NDLI is significantly correlated with foliar lignin concentration. Serbin et al. (2013) found that the CAI targets spectral region surrounding absorption features in the shortwave infrared that is associated with oxygen-hydrogen bending and carbon-oxygen stretching in cellulose and lignin.

The spectra for the extruded TPC, after accelerated weathering is shown in Figure 3. The color change is a relatively simple assessment by visual assessment. The color of WPCs primarily reflects the contribution to discoloration through physical mechanisms in the wood during weathering and water exposure. The spectral measurement can further assess the strength of the material through surface reflectance changes. The spectral changes in the visible range (400 – 750 nm), at 500 – 2000 h treatments, approximated that of reflectance, and there was a shifting at 3000 h, similar to the trend of $\triangle L^*$. The changes in NDVI, NDLI, NDNI and CAI for TPCs during weathering exposure are shown in Table 2. The NDVI value (0.0909 – 0.0072) for TPCs initially decreased as exposure increased from 0 to 500 h. The NDVI, NDNI and CAI for TPC without weathering were significantly higher than those for other samples with different weathering times. There was a variation in NDVI for different exposure durations: 0 h (0.0909) > 500 h (0.0072) > 1000, 2000 and 3000 h (-0.0046 to -0.0002). However, there were no statistically significant differences between different exposure durations (1000 h – 3000 h). The results showed that the deterioration of TPC can be established to estimate board density using NDVI. The changes in NDLI, NDNI and CAI for TPCs during exposure to weathering were 0.0072 (0 h) to 0.0059 (3000 h), -0.0101 (0 h) to -0.0053 (3000 h) and -0.0016 (0 h) to -0.0024 (3000 h), respectively. There were no statistically significant differences between different exposure durations (500 to 3000 h).

In this study, the deterioration of TPC was used to estimate board density by NDVI spectroscopy. The NDVI had a significant effect on caffeine content and chlorophyll content (Henik 2012, Dutta 2013). Some of the tea leaf flour in the surface of TPC board were removed when the

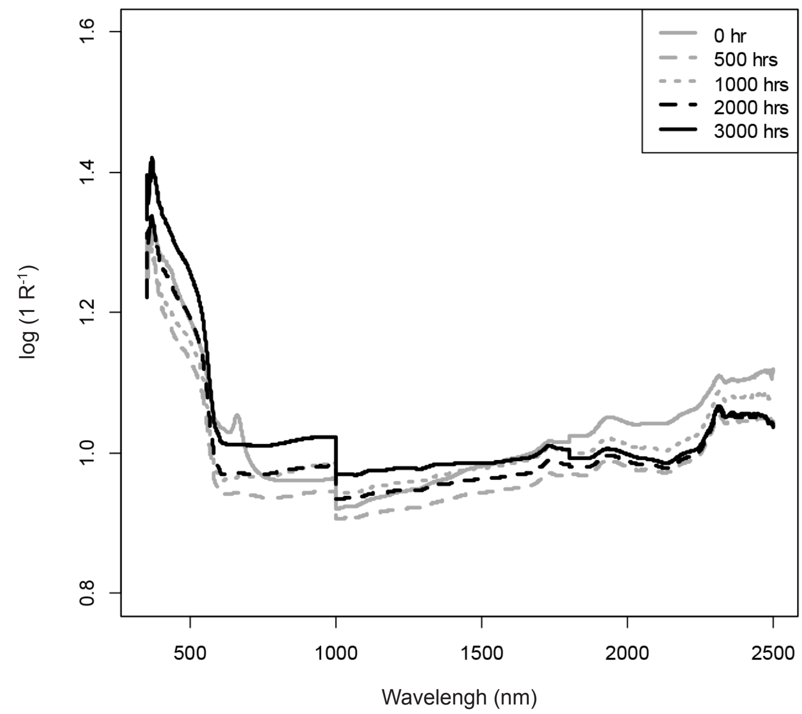

Figure 3 Spectra of the extruded tea leaf-plastic composite after accelerated weathering; R is spectral reflectance

Table 2 Changes in the NDVI, NDLI, NDNI, and CAI values of tea leaf-plastic composites as a function of accelerated UV weathering time

Treatment times	NDVI		NDLI		NDNI		CAI	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
0 h	0.0909	(0.0166) c	0.0072	(0.0010) c	-0.0101	(0.0031) a	-0.0016	(0.0005) c
500 h	0.0072	(0.0043) b	0.0070	(0.0007) c	-0.0061	(0.0012) bc	-0.0021	(0.0004) b
1000 h	-0.0046	(0.0078) a	0.0069	(0.0009) bc	-0.0070	(0.0015) b	-0.0021	(0.0004) b
2000 h	-0.0030	(0.0069) a	0.0064	(0.0008) ab	-0.0059	(0.0015) bc	-0.0022	(0.0003) ab
3000 h	-0.0002	(0.0033) a	0.0059	(0.0006) a	-0.0053	(0.0012) bc	-0.0024	(0.0002) a

Numbers in the parentheses indicate standard deviation (SD); different letters (a, b, and c) in the column indicate a significant difference at the 0.05 level by ANOVA and Turkey's test; n = 30

samples were exposed to UV light and water. Figure 3 shows a significant difference for chlorophyll absorption at wavelength 680 nm in TPC. The log-transform spectral peak for TPC without weathering was significantly different from other samples with different weathering durations.

Regression analysis between spectral characteristics and flexural properties

The results of the linear regression models between spectral characteristics and flexural properties (D, MOE and MOR) are shown in Table 2. There were significant positive relationships between NDVI and D or MOE. The determination coefficients (R^2) were 0.54 and 0.42, respectively ($p < 0.001$). The NDVI is the most important factor in determining D or MOE. Dutta (2013) reported that there is a significant effect on caffeine, catechin, epicatechin and epigallocatechin when NDVI was used as an explanatory variable.

To gain a better understanding of the relationship between spectral characteristics and flexural properties, the output was fitted to a curve using multivariable models. The spectral characteristics included NDVI, CAI, NDLI and NDNI, while the flexural properties included D, MOE and MOR. A stepwise regression procedure was used to acquire the most suitable multiple linear regression that predicts various mechanical properties. Table 2 shows that both NDVI and NDLI values gave the best prediction for D using multiple linear regression ($R^2 = 0.60$, $p < 0.001$). It was noted that the reflectance may be limited to detecting surface changes, resulting in poor model performance. Generally, this spectroscopic approach delineated surface texture well but had relatively low sensitivity in detecting change of material composite.

CONCLUSIONS

The study concluded that prior to weathering tests, the surfaces of the TPCs were smooth, but after the weathering tests, different severities of cavities were observed. The surface characteristics of TPCs also changed significantly after weathering. The Δa^*, Δb^* and ΔE^* values for TPC surfaces increased as exposure duration increased. The results indicated that exposure of TPC surfaces to weathering resulted in color darkening. The average D, MOE and MOR for TPCs without weathering were significantly larger than those for TPCs with different weathering (500 – 3000 h). The majority of flexural changes in D, MOE and MOR occurred during the first 500 h. The NDVI for TPCs decreased as the exposure duration increased (from 0 h – 500 h). The NDVI for TPC without weathering was significantly higher than those for other samples with different weathering times. However, there were no statistically significant differences between different exposure durations (1000 – 3000 h). The deterioration of TPC was used to estimate the board, using the change in NDVI. The NDVI was the most important factor in determining D or MOE. Both NDVI and NDLI gave the best prediction of D, using multiple linear regression ($R^2 = 0.60$, $p < 0.001$). A comparison with the changes in lightness, total color and flexural properties in WPC showed that TPC had better lightening, color and flexural stability.

Table 3 Correlations between the spectral characteristics (NDVI, NDLI, NDNI and CAI) and flexural properties (D, MOE and MOR) analysed by linear regression formulae

y	a	x_1		x_2		x_1*x_2		Model	R^2	p
Density	($p < 0.001$)	NDVI	($p < 0.001$)					$y = 1.14 + 0.29*x_1$	0.54	< 0.001
MOE	($p < 0.001$)	NDVI	($p < 0.001$)					$y = 1.53 + 2.78*x_1$	0.42	< 0.001
MOR	($p < 0.001$)	NDVI	($p < 0.001$)					$y = 16.81 + 20.55*x_1$	0.07	< 0.001
Density	($p < 0.001$)	NDLI	($p < 0.001$)					$y = 1.11 - 6.10*x_1$	0.14	< 0.001
MOE	($p = 0.867$)	NDLI	($p = 0.104$)					$y = 1.25 - 54.01*x_1$	0.09	< 0.001
MOR	($p < 0.001$)	NDLI	($p = 0.507$)					$y = 18.6 - 200.59*x_1$	0.01	0.507
Density	($p < 0.001$)	NDNI	($p < 0.001$)					$y = 1.12 - 3.18*x_1$	0.29	< 0.001
MOE	($p < 0.001$)	NDNI	($p < 0.001$)					$y = 1.37 - 33.81*x_1$	0.25	< 0.001
MOR	($p < 0.001$)	NDNI	($p = 0.115$)					$y = 16.23 - 142.33*x_1$	0.01	0.115
Density	($p < 0.001$)	CAI	($p = 0.115$)					$y = 1.18 + 17.04*x_1$	0.25	< 0.001
MOE	($p < 0.001$)	CAI	($p = 0.268$)					$y = 1.98 + 180.41*x_1$	0.23	< 0.001
MOR	($p < 0.001$)	CAI	($p = 0.398$)					$y = 18.39 + 537.24*x_1$	0.01	0.398
Density	($p < 0.001$)	NDVI	($p = 0.015$)	NDLI	($p < 0.001$)	NDVI*NDLI	($p = 0.671$)	$y = 1.12 + 0.32*x_1 - 4.29*x_2 - 8.23*x_1*x_2$	0.60	< 0.001
MOE	($p < 0.001$)	NDVI	($p = 0.101$)	NDLI	($p = 0.008$)	NDVI*NDLI	($p = 0.874$)	$y = 1.32 + 2.91*x_1 - 35.32*x_2 - 40.57*x_1*x_2$	0.43	0.216
MOR	($p < 0.001$)	NDVI	($p = 0.319$)	NDLI	($p = 0.349$)	NDVI*NDLI	($p = 0.674$)	$y = 18.96 + 46.74*x_1 - 326.70*x_2 - 2861.35*x_1*x_2$	0.07	0.003

y = response variable (flexural properties: Density, MOE, or MOR) of linear or multiple regression, a = p value of constant of linear or multiple regression, x_1 = first explanatory variable (spectral characteristics: the NDVI, the NDLI, the NDNI, or the CAI) of linear or multiple regression, x_2 = second explanatory variable (spectral characteristics: the NDVI, the NDLI, the NDNI, or the CAI) of multiple regression, x_1*x_2 = interaction term of multiple regression

ACKNOWLEDGEMENTS

This work was supported by a research grant from the Taiwan Forestry Research Institute of the Council of Agricultural.

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