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Research article

Sugarcane Yield Estimation Using UAV-Based RGB Images and Allometric Equations

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Abstract

Accurately estimating pre-harvest sugarcane yield has long been a challenge. There are many methods for predicting sugarcane yield, ranging from simple empirical equations to complex physiological models. This paper reports a study on a method for predicting sugarcane yield using allometric equations combined with UAV-based RGB images (UAVI). UAVI were used for the estimation of the sugarcane height, which is in the form of the sugarcane height model (HM). Sugarcane height is one of the key factors in calculating sugarcane yield in the allometric equation. The results showed that the HM could be used in the allometric equation. There was only a slight discrepancy compared to measurement with a tape measure in the field. In developing the allometric equation, the authors created regression models to estimate aboveground biomass weight in leaf bush (W_l) and millable stalk (W_{ms}) based on sugarcane height (H) and diameter measured from the first segment of sugarcane aboveground (D_{fs}). The model estimated aboveground biomass weight sufficiently for all stages of cultivation. Based on this model, the authors developed two general equations: $Y = 0.0842\ H * D_{fs}^{0.9827}$; $R^2 = 0.93$ (used for leaf bush), and $Y = 0.1254\ H * D_{fs}^{1.3926}$; $R^2 = 0.93$ (used for millable stalk). The decision correlation coefficient (R^2) was 80% reliable. The HM models were slightly different from field measurements with a tape measure. Also, there was a little inaccuracy in the root-mean-square error (RMSE) between the sugarcane heights analyzed from UAVI and field measurements using tape measure. The RMSE values, arranged from highest to lowest according to the sugarcane growth stage were: 0.35 m (tillering phase, T_P), 0.25 m (grand growth phase, G_P), and 0.24 m (ripening phase, R_P). Using the HM value in the allometric equation effectively estimated the sugarcane yield at different growth stages. Sugarcane growth at T_P and G_P phases gave the highest sugarcane yield at 200 cm of the HM value, with total yields of 11.49 and 16.75 ton/hectare, respectively. Whereas, R_P gave the highest sugarcane yield at 350 cm of the HM value (total yield at 42.97 ton/hectare). Overall, an accurate estimation of the aboveground biomass of leaf bush and millable stalk can be obtained using these equations. The authors believe that the research methods presented here can help sugarcane farmers to better estimate yield prior to harvest.

Keywords: pre-harvest sugarcane yield; UAV-based RGB image; sugarcane height model; allometric equation

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1. Introduction

Sugar is a plant-based sweetener that is in high demand worldwide both for direct consumption and as a flavoring agent in various products (Sowcharoensuk, 2021). There are two types of plants commonly used in sugar production: sugarcane and sugar beet, which are grown in different climates around the world (Figure 1). Sugarcane belongs to the genus *Saccharum*, the tribe Andropogoneae, and the family Gramineae. It is a large strong-growing species of grass that grows in temperate to tropical climates. It is also the main sugar-producing tropical crop in the world (Bajaj & Jian, 1995). Whereas sugar beet belongs to the subspecies *Beta vulgaris* L. subsp. vulgaris and forms a highly concentrated sucrose root crop that is grown commercially to produce sugar that thrives in cold and humid climates (Romeiras et al., 2016; Ogunsola et al., 2021). Sucrose is extracted from sugarcane or sugar beet and then dried to form natural sugar crystals.

In 2019, the most widely used natural sweeteners were white and brown sugar, making up 65.7% of all sweeteners used worldwide. The remaining 34.3% was artificial sweeteners, including aspartame, cyclamate, and erythritol (Sowcharoensuk, 2021). Thailand has tangibly promoted sugarcane cultivation, resulting in a planted area that nearly doubled from 1.0 million hectares in 2010 to 1.9 million hectares in 2019 (Sowcharoensuk, 2021). This is one of the main reasons why Thailand has become the world's third largest exporter of sugarcane products (Ogunsola et al., 2021; Shahbandeh, 2022). In 2016, sugarcane cultivation accounted for approximately 8% of the country's agricultural land (Figure 2). It is cultivated throughout almost every region of the country and its cultivation is especially concentrated in the northern, central, northeastern and eastern areas. In the last 10 years (2023-2024), sugarcane cultivation statistics have shown that the provinces of Udon Thani (located in the northeast), Kanchanaburi (located in the central region), Nakhon Sawan (located in the north), and Sa Kaeo (located in the east) are considered to be Thailand's top producing areas for sugarcane (Sowcharoensuk, 2021; Office of the Cane and Sugar Board, 2024). In addition, sugarcane farming also creates jobs for more than 1.5 million people.

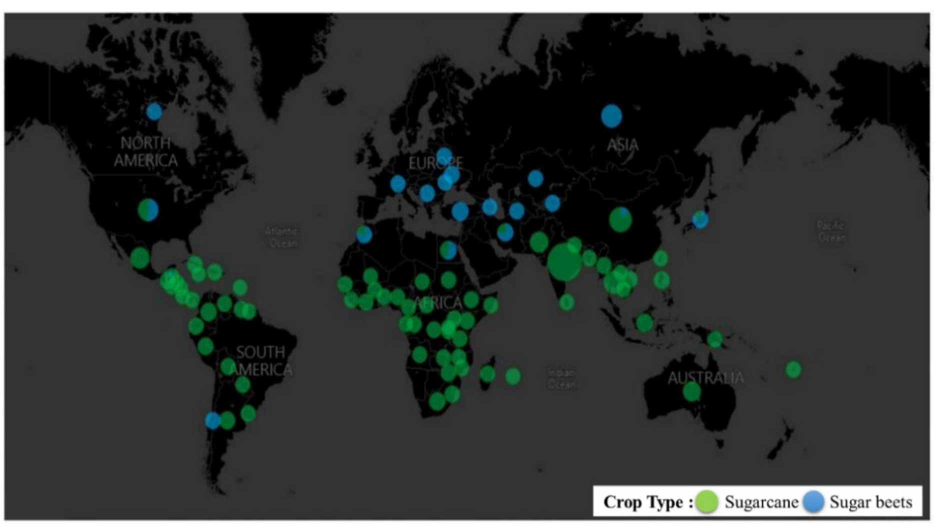


Figure 1. The main growing regions for the cultivation of sugarcane; (green circles), and sugar beets (blue circles) (Ogunsola. et al., 2021)

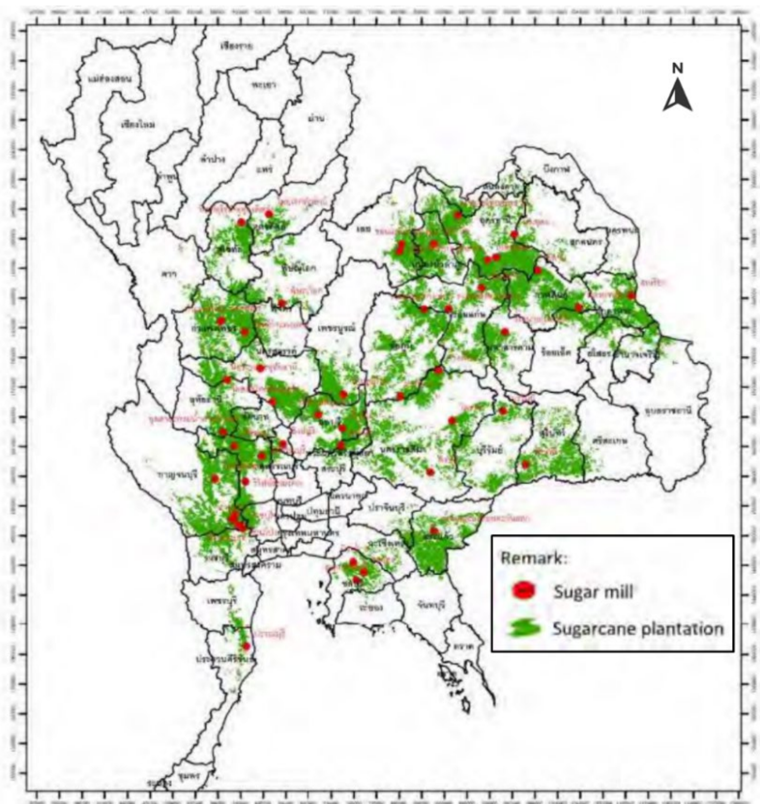


Figure 2. The location of sugarcane plantations and sugarcane mills in Thailand (Manivong & Bourgois, 2017)

While the production of sugarcane is of great importance, accurately estimating pre-harvest sugarcane yield has long been a great challenge. Estimates require a lot of time, labor, and expertise of appraisers (Office of the Cane and Sugar Board, 2015; The The ISAAN Record, 2019; Bunruang & Kaewplang, 2021). This issue also greatly affects the cost of production and the profitability of trading. The sugarcane harvest season runs from December to March. This is the period when the percentage of extractable sugar (commercial cane sugar, C.C.S.) is the highest (Chiadamrong & Kawtummachai, 2008). There are many methods for predicting sugarcane yield from simple empirical equations to complex physiological models. However, most of these prediction systems are limited to specific regions and time periods (Gunnula et al., 2012). Monitoring agriculture from space to assess pre-harvest crop yields has been the subject of research since the early 1970s (Wall et al., 2007). Scientists have applied techniques using remote satellite imagery such as MODIS, NOAA and AVHRR to predict crop yields (Som-ard et al., 2018). However, these methods were only moderately successful due to insufficient image spatial resolution (Prasad et al., 2006; Som-ard, 2018).

Unmanned aerial vehicles (UAVs) are therefore being used to solve such problems. UAVs are aircraft that can fly autonomously or semi-autonomously and are commanded by an assistant controller at a nearby geographic location (Daud et al., 2022). In the last decade, UAVs have become important instruments in remote sensing and in the monitoring of agricultural growth. Aerial imagery from UAVs is suitable for a wide variety of agricultural applications. This is due to improved spatio-temporal resolution, less susceptibility to potential obstruction (e.g., cloud cover) as well as relatively lower cost, and less complex operations (Som-ard et al., 2018; Sofonia et al., 2019; Tsouros et al., 2019). UAVs can be used to mount high potential aerial cameras for vegetation mapping and agricultural purposes. Because they can fly at low altitudes, UAVs make it possible to capture images with ultra-high spatial resolution, which enables rapid analysis of plant growth (Xiang & Tian, 2011; Han et al., 2019; Na et al., 2019). Many researchers are also studying various types of cameras or sensors in combination with UAVs for high-precision agricultural applications. The obvious examples are: RGB (red, green and blue) camera, multispectral sensor, hyperspectral sensor, and laser scan (Herwitz et al., 2004; Anthony et al., 2014; Bendig et al., 2014; Adão et al., 2017). UAV images from RGB cameras are rarely used for crop treatment and classifying crop rows. UAV-based RGB images (UAVI) show only the greenness of vegetation, which makes them less sensitive to yield and plant health issues (Xiaoqin, 2015).

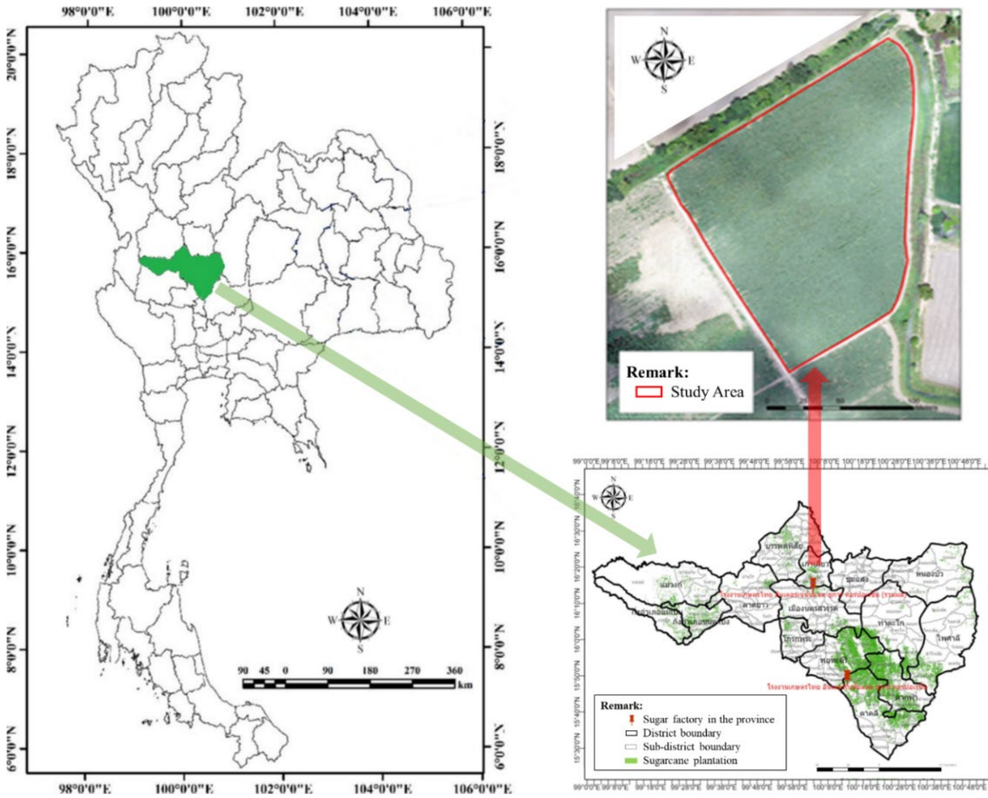
The harvesting method, which is a destructive method, is the most accurate method of estimating yield. However, farmers are unable to predict the yield at each plant growth stage. Therefore, methods for determining progressive yield increases in fields without cutting plants are considered a valuable tool for farmers. For the estimation of biomass or crop yield in a non-destructive way, allometric equations have been used in several areas (Antunes et al., 2008; Paul et al., 2013). The principle of an allometric equation is that, from certain parts of the plant, such as plant height and plant circumference or diameter, total plant growth can be calculated (Paul et al., 2013). Therefore, a non-destructive allometric equation approach is one of the best alternatives. Such approaches have mainly been used to estimate forest biomass and carbon stock (Pati et al., 2012; Vashum & Jayakumar, 2012). Moreover, allometric equations for estimating sugarcane yield have not often been found in the literature (Youkhana et al., 2017).

The use of UAVs in spatial variance analysis for accurate agricultural management has been found to be convenient, fast, and timely in critical times of plant growth. Therefore, this research aimed to use UAVs with an RGB camera to estimate sugarcane yield before harvesting. Herein, UAVI were used to assess the proportion and distribution of the sugarcane heights. These are two of the important factors for calculating sugarcane yield in an allometric equation. This technique can provide more options for evaluating sugarcane yields with greater accuracy.

2. Materials and Methods

2.1 Study area

In northern Thailand, sugarcane is grown in nine provinces: Phrae, Uttaradit, Sukhothai, Tak, Phitsanulok, Kamphaeng Phet, Phichit, Nakhon Sawan, and Phetchabun. Nakhon Sawan province has the largest sugarcane planting area (Office of the Cane and Sugar Board, 2024). Therefore, the study area chosen was in Hua Dong sub-district, Kao Liao district, Nakhon Sawan province in the northern part of Thailand (Figure 3).



Adaptation map from Som-ard et al. (2018) & Office of the Cane and Sugar Board (2024)

Figure 3. Study area map (Left: Location of study area in Thailand, Lower Right: Location of study area in Nakhon Sawan province map and Upper Right: Sugarcane plantation in UAVI)

2.2 Field data collection

This research was conducted in cooperation with Kaset Thai International Sugar Corporation Public Company Limited (Branch 3, Nakhon Sawan province) in the use of the company's sugarcane cultivation. The sugarcane cultivar used in this research was KK07-250, which has outstanding characteristics of yield and height, good stump, and displays medium resistance to black smut and red rot wilt (Ormzubsin et al., 2019). The study area consisted of 2.83 hectares or 28,300 m^2 of sugarcane plantations and the GPS coordinates were 15°53'33.4"N 100°05'51.6"E. In terms of physical characteristics, it is a flat area with a slope of less than 3 % and a soil depth of more than 50 cm. This is consistent with the recommendations for suitable areas for sugarcane cultivation of the Field Crops Research Institute (Field Crops Research Institute, 1983), Blackburn (Blackburn, 1984), and Bakker (Bakker, 1999). The sugarcane was planted in a single row using a machine with a distance of 1.5 m between the rows. There was only one cycle of sugarcane cultivation during this research. This was due to the fact that the sugarcane variety used as an experimental variety had not yet been planted for harvesting.

According to de Carvalho et al. (2019), the optimum area for sampling plots is 100 m^2. The total sugarcane plantation area for this research was 2.83 hectares or 28,300 m^2. Therefore, the measurement area was divided into 2 areas to try to cover the total sugarcane plantation area, as shown in Figure 4.

There were five variables for the field measurement parameters: 1) the sugarcane height (H), leaf bush (H_l) and millable stalk (H_{ms}), measured with a tape measure, 2) the diameter of the first segment of sugarcane aboveground (D_{fs}), measured with a vernier caliper, 3) the average number of stalks (N), calculated from a planting area of 100 m^2, by counting every stalk in the planting area, 4) the distance between sugarcane planting rows (S), measured with a tape measure, and 5) the weight of sugarcane aboveground biomass, leaf bush (W_l) and millable stalk (W_{ms}), measured by weighing method. For H, D_{fs}, S, W_l, and W_{ms} parameters, five sampling points were set up with each point measured 3 times. The points were divided between the four corners of the planting area and one on the central part of the field.

2.3 UAV-based data collection

In this process, UAV operations were divided into two types: flight planning and aerial photographic data collection. The flight paths were at an altitude of 90 m and in line with the growth of the sugarcane. Aerial photographic data collection was divided into 3 phases of sugarcane growth: tillering phase (180th day of cultivation), grand growth phase (227th day of cultivation), and ripening phase (298th day of cultivation). Data collection occurred between 11:00 PM and 1:00 PM. The integration of aerial photography is crucial for the creation of high-quality 3D models and orthoimages. The shooting pattern was designed so that the photos were overlapped by 80% in front and 60% on the side, which gave a pixel resolution of 2 cm. Another consideration in flight planning was the ground sampling distance (GSD). GSD is the spatial distance that represents one pixel on the image. The smaller the value of GSD is, the greater the spatial resolution of the photo and the more clearly visible details are. In addition, shooting from lower altitudes reduces distortion in aerial photographs and reduces GSD (Amphawan, 2018). The Pix4Dmapper program was used for UAV photography flight planning by automating grid-based flight for mapping. The UAV flew for at least 15 min at a time and took pictures in the visible RGB. The details of the UAV flight planning and flight configuration are shown in Figure 5.

Aerial photographic data collection using direct and indirect pointer targets, where the images were taken in at least two metric formats. Aerial photographic data activity included collecting plot coordinates and adjusting reflectivity. To determine the topographical coordinates, six ground control points (GCPs) were set, which acted as intermediaries that allowed the images to be related to the reference (Boonlua et al., 2021). In addition, GCP data used GNSS RTK to collect coordinates. GCP allows aerial imagery to be recorded relative to the terrain coordinate system (TCS), which is divided into horizontal control points and vertical control points. TCS are generally divided into (1) horizontal coordinates; geographic coordinate system (latitude and longitude), grid coordinate system (UTM Easting, Northing (N, E)), and (2) vertical coordinates; Mean Sea Level (MSL) and Signalized Point (Amphawan, 2018). Next, image processing was divided into: geometry correction and radiography > orthomosais > digital surface modeling > cane height analysis. Finally, an accuracy assessment was done and a high-detailed map of the sugarcane was created in a digital format that could be displayed in the GIS (Spatial Database).

Figure 4. Determination of the area for field parameter measurements

Figure 5. Planning and configuration characteristics of UAV flight

2.4 Aerial photographic processing

The Pix4 D Mapper program was used to process aerial photographs. The differences between the Digital Elevation Model (DEM) and the Digital Surface Model (DSM) were used to create a digital elevation 3D model. Aerial photographic processing with Pix4D mapper included the following main steps: creation of a project > addition of images to the project that included information such as coordinates and height above sea level > selection of coordinate values for the results of processing > selection of processing type

> processing. However, the processing method had to be point cloud-based in order to obtain the ground layer. The point cloud classification results were divided into 5 levels: Ground, Road Surface, High Vegetation, Building, and Human Made Object. Only variables showing the separation of data layers, such as high vegetation and ground, were selected for this research. Next, these variables were used to calculate the sugarcane height equation.

Sugarcane height was calculated using images from the UAV. The processed images were assessed for accuracy. The accuracy assessment was done by referring the GCP coordinates to an image, and adjusting it to fit the reference coordinates. The Pix4D Mapper analyzes Digital Surface Models (DSM) and Digital Terrain Models (DTM) to create 3D images of sugarcane height clusters in plantations. Point cloud classification was used in this processing to classify and layer the objects present in the model. The ground level was utilized to calculate the sugarcane height in the later stages. Then, the height model (HM) was analyzed using ArcGIS. The DEM is a numerical elevation model that only represents the Earth's surface or topography. However, the DSM is a numerical surface model that shows the surface characteristics of land cover such as buildings or the canopy of trees. In this research, the DSM showed the surface characteristics of sugarcane height. The DTM is a model of the area's physical surface height, which includes the covering of the earth's physical surface or Digital Terrain. As a result, the height obtained is not the height obtained from the actual surface condition of the earth. The actual height of the surface needs to be adjusted by modifying the height model (DEM editing). The results can then be used to generate contour lines. The sugarcane Height Model (HM) was ultimately developed through the generation of DSM and DTM, utilizing the equation presented as equation (1).

$$\text{NDSM or HM} = \text{DSM} - \text{DTM} \tag{1}$$

Note: DTM = Digital Terrain Model
DSM = Digital Surface Model
NDSM = Normalized Digital Surface Model
HM = Height Model

Further, the validation of the HM was performed using the root-mean-square error (RMSE) equation according to equation (2).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[Estimated\ value - Observed\ value]^2} \tag{2}$$

Note: RMSE = root-mean-square error
Estimated value = Height value from HM
Observed value = Height value from field measurements (FM)
n = Total amount of data

Finally, the sugarcane height data from the HM were compared with field measurements (FM) using correlation equation (3).

$$R^2 = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{3}$$

Note: R^2 = Correlation coefficient
x = Height value from HM at i to n
y = Height value from FM at i to n
$\bar{x}$ = Average height from HM
$\bar{y}$ = Average height FM

2.5 Estimation of sugarcane yield by allometric equation

Sugarcane yield was estimated using allometric equations combined with the HM from equation (1). The principle of allometric equations for estimating sugarcane yields are based on research by de Carvalho et al. (2019). Details of the equation are as follows:

$$Y = a * H * D_{fs}^{b} \quad (4)$$

Note: Y = Sugarcane yield (Kg)
H = The plant height measured with a tape measure (H, cm.)
D_{fs} = Diameter measured from the first segment of sugarcane aboveground (cm)
a, b = Equation constant

In addition, sugarcane yield per unit area was calculated according to equation (5).

$$ScY = [Y \times (N/S)] \quad (5)$$

Note: ScY = Sugarcane yield per unit area (ton/hectare)
Y = Sugarcane yield calculated according to the equation (4) (Kg)
N = The average number of stalks as calculated from a planting area of 100 m^2
S = The distance between the sugarcane planting rows (cm)

3. Results and Discussion

3.1 Sugarcane height analysis

The UAV-based RGB images (UAVI) of the sugarcane fields were analyzed to determine the sugarcane height, as was done by de Souza et al. (2017). A 3-dimensional model of sugarcane height was created from the extraction of crop surface model (CSM) by subtracting the digital surface model (DSM) and digital terrain model (DTM) from UAV data. Both the DSM and DTM were processed based on a structure from motion (SfM) photogrammetry approach. The sugarcane height values obtained from these models were slightly different from field measurements with a tape measure. The root-mean-square error (RMSE) between sugarcane height analyzed from the UAVI and field measurements with a tape measure was arranged in descending order according to growth phase of sugarcane as follows: 0.35 m (tillering phase), 0.25 m (grand growth phase), and 0.24 m (ripening phase).

Sugarcane (*Saccharum spp.* L.) is a semi-perennial plant and its growth cycle is usually 12 to 18 months before harvest. The growth cycle is different for each country. It depends mainly on the following factors: sugarcane variety, climate and local geography (Rudorff et al., 2010; Prasara-A et al., 2016). Sugarcane stalk has the particular capacity to store a crystallizable sugar, sucrose, in an amount between 10%-15% by weight of the stalk. The juice is first extracted from the sugarcane stalk by tandem milling or diffusion and converted to pure sucrose (raw sugar) at factories (Eggleston & Lima, 2015). This research focused on measuring the height of the sugarcane stalk, which is an important part of evaluating sugarcane yield. Yu et al. (2020) found that UAV-derived crop height could facilitate better yield estimates when data was included in crop growth models. UAVI can be converted to a Height Model (HM), converted to a Height Model (HM), which solely indicates the total height of the cane or the height of the canopy. Therefore, the authors compared the HM with the sugarcane height ratio obtained from field measurements. The sugarcane height ratio was calculated as follows: 1 (leaf bush): 1.5 (millable stalk). A comparison of sugarcane height in different sections calculated by the UAV and field measurements is presented in Table 1.

Table 1. Comparison of sugarcane height in different sections calculated from UAV and field measurements

Parameter	The Sugarcane Growth Stage [1/]					
	Tillering Phase		Grand Growth Phase		Ripening Phase	
	UAV	Field [2/]	UAV	Field [2/]	UAV	Field [2/]
1. Sugarcane height (m) [3/]						
- Canopy height	3.17 ±0.52 [4/]	2.88 ±0.53	3.40 ±0.45 [4/]	3.19 ±0.44	3.28 ±0.50 [4/]	3.12 ±0.52
- leaf bush (H_l)	1.27 ±0.21 [5/]	1.15 ±0.21	1.36 ±0.18 [5/]	1.28 ±0.18	1.31 ±0.20 [5/]	1.25 ±0.21
- millable stalk (H_{ms})	1.90 ±0.31 [5/]	1.73 ±0.32	2.04 ±0.27 [5/]	1.91 ±0.27	1.97 ±0.30 [5/]	1.87 ±0.31
2. R^2 [6/]						
- Canopy height [7/]	0.85		0.85		0.81	
3. RMSE						
- Canopy height [7/]	0.35		0.25		0.24	

[1/] The growth stage of sugarcane is not measured from the germination phase because at this stage there is no growth until the characteristics of the stalk and the leaf bush can be clearly distinguished.
[2/] Field measurement with tape measure.
[3/] Values are expressed as mean and ± standard deviation.
[4/] Analysis and evaluation from the UAVI only.
[5/] Analysis and evaluation from the UAVI combined with field measurements with a tape measure.
[6/] The decision correlation coefficient (R^2) was 80% reliable.
[7/] The R^2 and RMSE of the sugarcane height only were calculated because it is the height from the UAV that will be used in the next analysis of sugarcane yield.

3.2 Estimation of sugarcane yield by allometric equation

3.2.1 Development of allometric equations

Determining sugarcane yield using allometric equation involves finding the relationship between physical growth (i.e. H and D_{fs}) and sugarcane aboveground biomass weight (W) (i.e. W_l and W_{ms}). From the research of de Carvalho et al. (2019), the main parameters used for calculation of allometric equation were H and D_{fs}, where H varied with D_{fs} as the growth of sugarcane increased. Therefore, the development of the allometric equation involved the analysis of the relationship of the multiplication results of H and D_{fs} with W. The three parameters for the calculation of allometric equations are shown in Table 2.

Table 2. Three parameters for the calculation of allometric equations at different growth stages

Parameter	Sugarcane Growth Phases		
	Tillering (n = 36)	**Grand Growth** (n = 58)	**Ripening** (n = 30)
1. D_{fs} (cm)	2.72±0.26	3.25±0.14	3.71±0.20
2. H (m)			
- leaf bush (H_l)	1.15±0.21	1.28±0.18	1.25±0.21
- millable stalk (H_{ms})	1.73±0.32	1.91±0.27	1.87±0.31
3. W (kg)			
- leaf bush (W_l)	0.41±0.12	0.54±0.09	0.49±0.09
- millable stalk (W_{ms})	1.02±0.29	1.59±0.27	2.02±0.37

Values are expressed as mean and ± standard deviation.

The height and diameter of sugarcane tend to decrease due to climate change (Som-ard et al., 2021). The air temperatures during the experiment were approximately 36°C-40°C. The three parameters listed in Table 2 were used for correlation analysis using Excel, which led to the allometric equations in Table 3. The accuracy and precision of the allometric equations was determined from the coefficient of determination (R^2). The R^2 or the correlation coefficient of the multiplication results between H and D_{fs} with W had to be at least 0.8 (Daba & Soromessa, 2019), indicating a strong relationship between the variables for this research. The allometric equations according to the different growth stages of sugarcane are shown in Table 3.

Table 3. Allometric equations for estimating sugarcane yield

The Aboveground Biomass	The Allometric Equations [1/]	R^2 [4/]
1. Part of leaf bush		
- Tillering phase	$Y = 0.0551\ H * D_{fs}^{1.2829}$	0.94
- Grand growth phase	$Y = 0.0736\ H * D_{fs}^{1.0882}$	0.94
- Ripening phase	$Y = 0.0627\ H * D_{fs}^{1.0574}$	0.93
- General equation [2/]	$Y = 0.0842\ H * D_{fs}^{0.9827}$	0.93
2. Part of millable stalk		
- Tillering phase	$Y = 0.1420\ H * D_{fs}^{1.2655}$	0.94
- Grand growth phase	$Y = 0.2206\ H * D_{fs}^{1.0806}$	0.94
- Ripening phase	$Y = 0.2699\ H * D_{fs}^{1.0395}$	0.93
- General equation [3/]	$Y = 0.1254\ H * D_{fs}^{1.3926}$	0.93

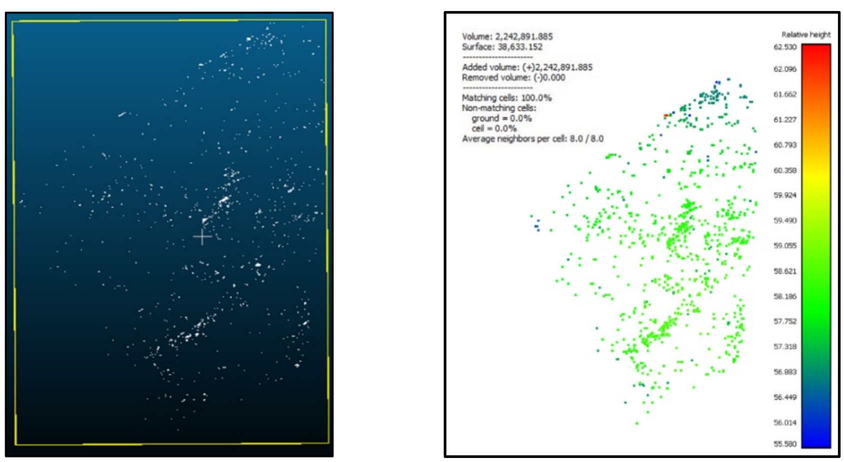
[1/]Substitution of the H value in the allometric equation was done by comparing the HM value with the measured sugarcane height ratio in the field, as follows: 1 (leaf bush) : 1.5 (millable stalk).
[2/]The general equation can calculate the yield of leaf bush at all stages of sugarcane growth. In addition, this equation also analyzes the relationship of the multiplication results of H and D_{fs} with W_l in all 3 growth stages (n= 124).
[3/]The general equation can calculate the yield of millable stalk at all stages of sugarcane growth. In addition, this equation also analyzes the relationship from the multiplication results of H and D_{fs} with W_{ms} in all 3 growth stages (n = 124).
[4/]A decision correlation coefficient (R^2) of 80% indicates reliability.

For sugarcane yield per unit area estimation, the calculation (according to the equation in Table 3, together with equation (5)) should consider the average number of plants in the planting rows (N) and the spacing between the rows (S). The measurement of N indicated that the average value was 4.73 stalks. For S, the length was 1.5 m. Row planting patterns are often designed based on genetics and influencing factors such as climate, sunlight, irrigation sources, treatment systems and soil properties (Garside & Bell, 2009). In addition, wider row spacing results in a significant increase in cane diameter compared to narrow spacing (Ahmed et al., 2011). The optimal row spacing is as important to high sugarcane growth as any other factor. The optimal row spacing for sugarcane growth was between 0.90-1.40 m (for single-row planting) and 1.20-1.80 m (for double-row planting) (Som-ard et al., 2021).

3.2.2 Sugarcane yield estimation

Prior to the use of allometric methods, we evaluated sugarcane yield (or aboveground biomass weight) with the Point Cloud Above Ground (PCAG) technique using the Pix4D mapper software. The results of the evaluation of aboveground biomass weight using the Pix4D mapper software are shown in Figure 6.

It appears that the aboveground biomass weight could only be estimated at the early stages of growth (the germination phase). A group of sugarcane heights up to 25 cm and 50 cm were classified by the finished software. The group of sugarcane seedlings at heights of 25 cm and 50 cm had an aboveground biomass weight of 0.81 tons/ha (85 % of the total cultivated area) and 0.13 tons/ha (15 % of the total cultivated area), respectively (Figure 7).



(A) (B)

Figure 6. The UAVI were translated by the finished software; (A) the image of sugarcane plantations interpreted by PCAG technique, and (B) the image of sugarcane plantations that have been assessed for aboveground biomass weight using the Pix4D mapper software.

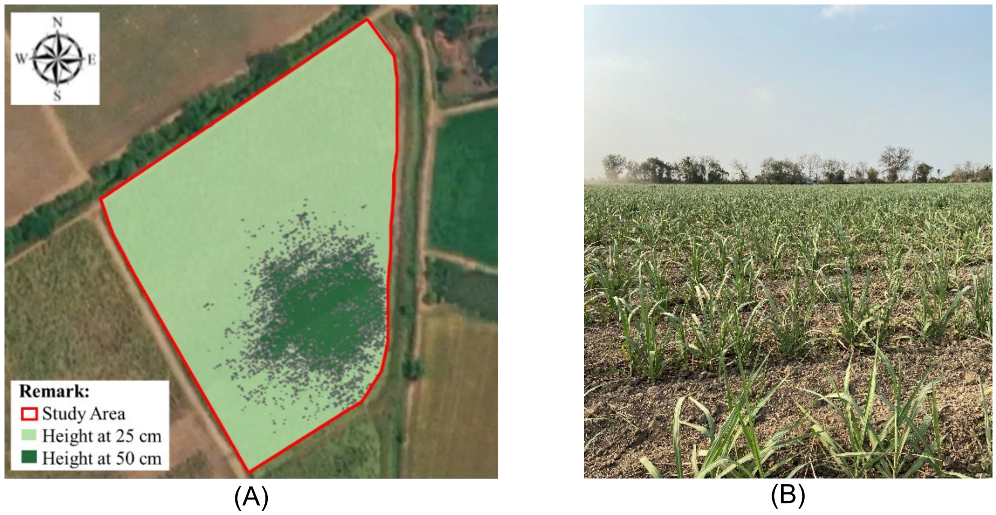


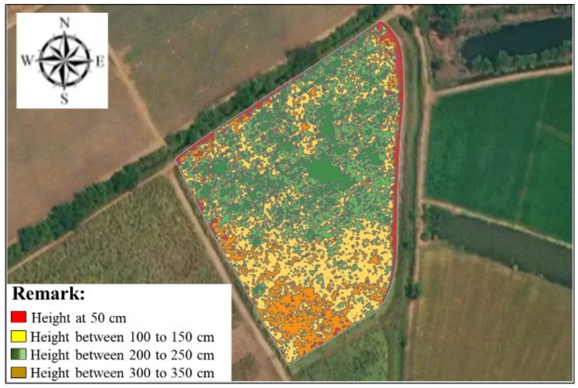
Figure 7. Sugarcane growth in the early stages of growth; (A) proportion and distribution of sugarcane height in the germination phase and (B) sugarcane growth in the study area

On the other hand, the PCAG technique was unable to efficiently analyze growth at other stages. This made the aboveground biomass weight estimates highly inaccurate. Therefore, this research used Pix4D mapping software to estimate the sugarcane height or HM at various growth stages (i.e. tillering phase, grand growth phase, and ripening phase). Figure 8 shows the proportions and distribution of sugarcane height at different phases.

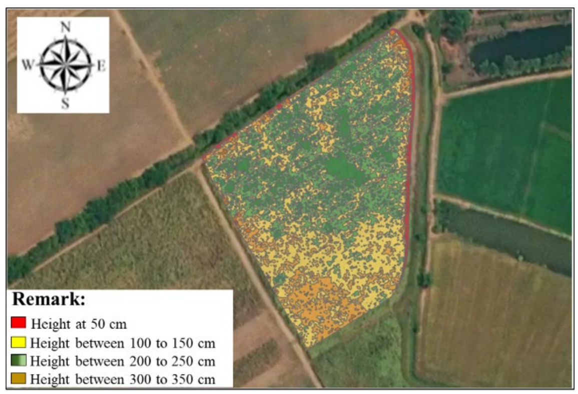
Figure 8 indicates that for tillering phase (A) and grand growth phase (B), the HM range was mainly between 200-300 cm (or 82% of the cultivated area). At HM ranges of 50-150 cm and 350-450 cm, the height proportions of sugarcane in cultivated area were 17.98% and 0.02%, respectively. In case of the ripening phase (C), the HM range was mainly between 350-450 cm (or 61.39% of the cultivated area). At HM ranges of 200-300 cm and 50-150 cm, the height proportions of sugarcane in cultivated area were 28.54% and 10.08%, respectively. These HM ranges were used in the allometric equations. The sugarcane yield estimation in this research was carried out in two parts: millable stalk and leaf bush (see Table 4 and Table 5).

From Table 4, using the HM value in the allometric equations effectively estimated the yields of sugarcane at different growth stages. Sugarcane growth at the tillering (T_P) and grand growth (G_P) phases gave the highest sugarcane yield at 200 cm of the HM value, with total yields of 11.49 and 16.75 ton/hectare, respectively. Whereas the sugarcane growth at the ripening phase (R_P) gave the highest sugarcane yield at 350 cm of the HM value (total yield at 42.97 ton/hectare). In addition, the evaluation of sugarcane yield by separating leaf bush (L) and millable stalk (S) also revealed that the yield (%) of S increased with the cultivation period, while the yield (%) of L decreased with the cultivation period.

The measurement of sugarcane height is very important for the evaluation of sugarcane yield. This research showed abnormal sugarcane height during the ripening phase. There were broken and fallen canes in several points in the cultivated area (Figure 9).



(A)



(B)

(C)

Figure 8. Sugarcane height processed from the UAV images; (A) tillering phase, (B) grand growth phase, and (C) ripening phase

Table 4. Evaluation of sugarcane yield at different growth stages

SG$_P$	Sugarcane Height Range (cm)[1/]											
	50 - 150				200 - 300				350 - 450			
	%$_{HM}$	Yield (t/h)			%$_{HM}$	Yield (t/h)			%$_{HM}$	Yield (t/h)		
		L	S	T		L	S	T		L	S	T
T$_p$	17.98	1.73	3.99	5.72	82.00	7.92	18.24	26.16	0.02	0.001	0.01	0.011
G$_p$	17.98	2.10	6.26	8.36	82.00	9.61	28.54	38.15	0.02	0.001	0.01	0.011
R$_p$	10.08	1.44	6.03	7.47	28.54	4.07	17.08	21.15	61.39	8.74	36.74	45.48

1/ = Analysis and evaluation from the UAVI only
SG$_P$ = Sugarcane growth phase
T$_P$ = Tillering phase
G$_p$ = Grand growth phase
R$_P$ = Ripening phase
%$_{HM}$ = The percentage of HM in cultivated area
Yield = Calculated according to the equation in Table 3, together with equation (5)
L = Aboveground biomass in part of leaf bush
S = Aboveground biomass in part of millable stalk
T = Total aboveground biomass weight (sum of S and L)
t/h = ton / hectare

Table 5. Overview of sugarcane yield at different growth stages

SG$_P$	Days after planting	Yield					
		L		S		T	
		(t/h)	(%)	(t/h)	(%)	(t/h)	(%)
T$_P$	180	9.65	30.26	22.24	69.74	31.89	100
G$_p$	227	11.71	25.17	34.81	74.83	46.52	100
R$_P$	298	14.25	19.23	59.85	80.77	74.10	100

SG$_P$ = Sugarcane growth phase
T$_P$ = Tillering phase
G$_p$ = Grand growth phase
R$_P$ = Ripening phase
Yield = Calculated according to the equation in Table 3, together with equation (5)
L = Aboveground biomass of leaf bush
S = Aboveground biomass of millable stalk
T = Total aboveground biomass weight (sum of S and L)
t/h = ton / hectare

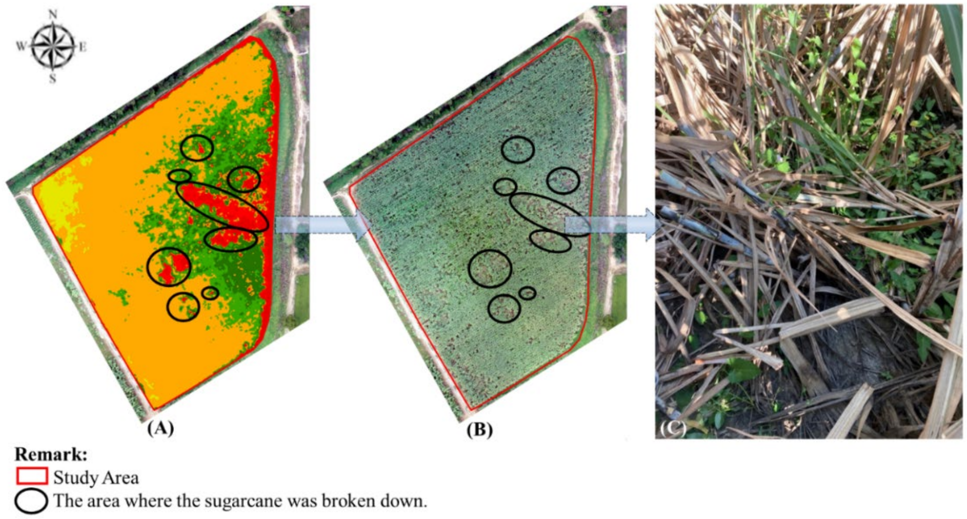


Figure 9. Sugarcane growth during ripening phase; (A) the simulated image shows an area with unusually short sugarcane heights, (B) the orthoimage showing falling and breaking of sugarcane, and (C) characteristics of the fallen and broken sugarcane

During the growth stage from the tillering phase to the grand growth phase, the sugarcane showed no damaged areas, whereas some patches of the sugarcane were broken down and overlapped in the ripening phase. Therefore, measuring and evaluating the canopy heights of broken and felled sugarcane in the field based on the UAVI led to inaccurate yield assessments. This is considered a limitation of this research. The erroneous assessment of sugarcane production from the UAVI was similar to the research of Nodthaison et al. (2019), where the study of sugarcane yield prediction using NDVI, $CI_{red\ edge}$ indices related to the extent of the Digital Surface Model (DSM) found that a large number of broken and fallen sugarcanes caused a very high inaccuracy in the sugarcane yield predictions.

4. Conclusions

Pre-harvest evaluation of agricultural produce is an important task in agricultural planning and decision-making management. In our approach, the sugarcane height model (HM) was used with the UAVI to substitute values in the allometric equation. Sugarcane height is one of the key factors used in calculating sugarcane yield in the allometric equation. The UAV images were also used to estimate the proportion and distribution of the sugarcane canopy height in the plantation area. Comparing the HM with the sugarcane canopy heights obtained from field measurements with a tape measure revealed that the obtained values were slightly different. Also, there was a little inaccuracy in the root-mean-square error (RMSE) between the sugarcane heights analyzed from UAVI and the field measurements using tape measure. These arranged from highest to lowest according to the sugarcane growth stage: 0.35 m (tillering phase, T_P), 0.25 m (grand growth phase, G_P), and 0.24 m (ripening phase, R_P). In addition, sugarcane yield per unit area was calculated. To develop the allometric equations, a regression model was created to estimate aboveground biomass weight in leaf bush (W_l) and millable stalk (W_{ms}) based on sugarcane height (H) and diameter measured from the first segment of sugarcane aboveground (D_{fs}). This aboveground biomass weight model was sufficient for all stages of cultivation. From the model, two general equations were emerged: Y = 0.0842 H * $D_{fs}^{0.9827}$; R^2 = 0.93 (used for leaf bush), and Y = 0.1254 H * $D_{fs}^{1.3926}$; R^2 = 0.93 (used for millable stalk). The equations produced decision correlation coefficient (R^2) of greater than 80%, showing their reliability. Using the HM values in the allometric equations could effectively estimate sugarcane yields at different growth stages. The sugarcane growth at the T_P and G_P phases had the highest sugarcane yields at 200 cm of the HM value, with total yields of 11.49 and 16.75 ton/hectare, respectively, whereas the R_P phase gave the highest sugarcane yield at 350 cm of the HM value (total yield at 42.97 ton/hectare). From the results, using the HM values in the allometric equations effectively estimated the yield of sugarcane at different growth stages. In addition, the evaluation of sugarcane yield by separating millable stalk (S) and leaf bush (L) also revealed that the yield (%) of S increased with cultivation period, whereas the yield (%) of L decreased with cultivation period. The UAVI also revealed abnormal canopy height during the ripening phase. There were broken and fallen sugarcanes at several points in the cultivated area. Therefore, measuring and evaluating the canopy heights of broken and felled sugarcane in the field via UAVI led to inaccurate yield assessments. However, the UAVI along with the allometric equations showed great potential for estimating sugarcane yield before harvest. This can also be used as another way to check the health of sugarcane.

The techniques discussed here require very little information compared to traditional and conventional methods. The data requirements are only the UAVI and ground survey data for height, diameter, number of stalks, and distance between the sugarcane planting rows. In addition, the precision of allometric equations was influenced by appropriate ground survey data. The accuracy of canopy height estimation largely depends on the accurate identification of sugarcane pixel areas. In conclusion, it is possible to help the sugarcane industry and farmers to estimate pre-harvest sugarcane yield using the approach discussed in this study.

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6. Conflicts of Interest

The authors declare no conflict of interest.

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