JGISE Vol. 8 No. 1 (2025), pp. 75 - 90 | https://doi.org/10.22146/jgise.99921

JGISE
Journal of Geospatial Information Science and Engineering
ISSN: 2623-1182 | https://jurnal.ugm.ac.id/jgise

Palm Oil Health Monitoring Based on VARI Vegetation Index using UAV

Baskara Suprojo[1], Luthfi Adela Saraswati[2], Fikri Ainur Rosyidi[2]

[1]*Kantor Wilayah Badan Pertanahan Nasional Provinsi Kalimantan Timur, Indonesia*
[2] *Sekolah Tinggi Pertanahan Nasional, Indonesia*

Corresponding Author: Baskara Suprojo **| Email:** baskarasuprojoo@gmail.com

Received: 12/09/2024 Revised: 13/06/2025 Accepted: 15/06/2025

ABSTRACT

The plantation sector has an urgency in technological renewal and development, especially in palm oil. Palm oil commodities are included in the staples needed by the Indonesian people for various products and as one of the sectors that generate the largest foreign exchange. Palm oil plantation management practices that have been carried out manually are less able to control plant health, especially during the pandemic which has caused severe impacts in Indonesia. The purpose of this research is to showcase the implementation of Smart Agriculture through the utilization of Unmanned Aerial Vehicle (UAV)/Drone technology in determining palm oil health. This research uses spatial analysis to detect the level of palm oil health by utilizing aerial photographs and GIS software with the Visible Atmospherically Resistant Index (VARI) method which can detect differences in the wavelength of the spectrum reflected by the plant canopy. This research is located in Argomulyo Village, Sepaku District, Penajam Paser Utara Regency, East Kalimantan Province, with abundant palm oil plantations. It was found that out of 2,167 samples of palm oil plants in the studied plantation, 14% were very unhealthy, 34.61% were unhealthy, 36.54% were healthy, and 14.85% were very healthy.

Keywords: Aerial Photography, Palm Oil Health, Smart Agriculture, VARI

1. Introduction

Technology is a tool that helps humans in facilitating various activities (Glover, 2022; Mirzaliev et al., 2022). The urgency of technological renewal and development has benefited various sectors of human work such as production, monitoring, distribution, and consumption processes (Hervas, 2021; Maddikunta et al., 2022). The plantation sector is one of the main sectors that have an urgency for technological needs (Pachayappan et al., 2020).

Palm oil plantations are the commodity that generates the largest foreign exchange for Indonesia through non-oil and gas export activities/commodity processing industry (Aryani et al., 2022; Syahfitri et al., 2022). The extent of legal palm oil plantations in Indonesia is one of the centers of attention and a form of government seriousness that this commodity is a main flagship export (Kementerian Perdagangan Republik Indonesia, 2021). In 2020, the beginning of the COVID-19 pandemic, the palm oil commodity experienced supply and demand instability which had an impact on losses, therefore the price of this commodity fluctuated (Nafisah & Amanta, 2022; Oktarina et al., 2022). Factly, Palm oil is one of the staples needed by the people of Indonesia and other countries for the food, cosmetic, and soap industry (Ernah & Tanaem, 2021; Muda et al., 2018) As a result, production, maintenance, and harvesting activities have experienced a decline because palm oils are starting to be poorly cultivated (Aryani et al., 2022; Nafisah & Amanta, 2022; Nurrizqi et al., 2022).

The process of managing palm oil plantations is still done manually and has been deeply affected by the pandemic. Damage to plants that are not easily detected, asymptomatic symptoms (Fatmayati et al., 2022), and the reduction of plantation managers aggravate the condition and reduce palm oil farming activities in Southeast Asia, especially Indonesia which is the most severely affected (Khuzaimah et al., 2022). The lack of progress in the management process and the minimal role of technology are among the factors in the urgency of palm oil plantations, especially smallholders in Indonesia (Dandi Bahtiar & Faraitody, 2022).

Technology continues to develop radically and intensively in organizing, overcoming, planning, and facilitating activities on a large scale, quickly, effectively, and cheaply (Sridhar et al., 2022; Xu et al., 2022). These advancements come together in agricultural production systems and smart farming, which is considered the connecting line between technology-based breeding, management, and harvesting (Klerkx et al., 2019; Suma, 2021). The digitalization of agriculture focuses on obtaining data on the status, location, state, disease, energy, irrigation conditions, and soil fertility using technological hardware such as UAV/Drone, sensor machines, and even satellites through continuous observation (Fountas et al., 2020; Lova Raju & Vijayaraghavan, 2020). Of course, precision agriculture in the smart farming agenda requires stakeholder involvement in the adoption of agricultural technology management (Salam & Shah, 2019).

Surveillance technologies such as UAV/Drone can monitor plantation conditions through aerial photography with a very wide range and capture spectral light reflected by palm oil plants (Gao et al., 2020; Kanning et al., 2018). UAV/Drone are a type of uncrewed aircraft that can be controlled through a remote controll system with radio waves or with pre-programmed objectives (Mohsan et al., 2022; Saroinsong et al., 2018; Andaru et al., 2024). UAV/Drone are capable of storing and taking pictures from a certain height to observe and manage plantations. Certainly, the advantage of UAV/Drone compared to satellites is that the operation is carried out directly and can be adjusted to the distance and height of flight using a controller, so that the resulting product has a higher spatial resolution by the Area of Interest (AOI), more flexible spectral resolution, and can be processed directly (Iizuka et al., 2018; Ren et al., 2019; Andaru and Santosa, 2017). By all means, palm oil information obtained through optical sensing and remote sensing mechanisms in detecting the presence of chlorophyll reflected directly by plants (Amirruddin et al., 2020; Izzuddin et al., 2020).

The aerial photography data is analyzed using a Geographic Information System (GIS) to determine the health level of the palm oil. GIS is a computer system for capturing, storing, analyzing, and displaying geospatial data (Lü et al., 2018; Supriadi & Oswari, 2020). GIS software such as ArcGIS and Agisoft can help manage crops by detecting the spectral reflection of color by leaf pigmentation and water content in the canopy through the vegetation index method, namely Visible Atmospherically Resistant Index (VARI) (Roth et al., 2023; Tayade et al., 2022). VARI can resist atmospheric disturbances in the color spectrum, so it can improve the vegetation index using the red-green-blue (RGB) spectral that is currently owned by all UAV/Drone cameras (Pollino et al., 2023; Raj et al., 2020).

Several previous studies have examined the use of photogrammetry, remote sensing, and vegetation indices in the agricultural sector including palm oil monitoring using the light spectrum on Worldview satellite imagery in Krabi Province, Thailand (Malinee et al., 2021), mapping of nipa plants in mangrove using satellite imagery (Numbere & Maimaitijiang, 2019), assessment of maize growth and development using remote sensing (Ballesteros et al., 2021), use of multispectral imagery for yield prediction and optimisation of maize (Barzin et al., 2020), estimation of maize grain yield using multispectral spectra from UAV (García-Martínez et al., 2020), research on soil temperature and drainage systems by utilising the capabilities of UAV in detecting hyperspectral and multispectral sensors (Khuzaimah et al., 2022; Andaru & Santosa, 2017), periodic monitoring of rice to detect growth inaccuracies and soil quality sensitivity with UAV and AI algorithms in the concept of smart farming in Pakistan (Hassan et al., 2022), as well as High-Throughput Phenotyping (HTP) and Multifaceted technologies in various plants with vegetation index approaches in analysing chlorophyll levels, aspects, and crop quality with remote sensing (Kurkute, 2018; Siregar et al., 2020).

Based on the above studies, the monitoring of palm oil still uses satellite images that have lower spatial and spectral resolution than aerial photographs, which has an impact on relatively low data credibility. In addition, low speed and lack of accuracy with an error rate of up to 15%, as well as require very high photo quality for maximum detection. The author uses UAV/Drone in observing palm oil health to provide good accuracy and precision in the reduction and prevention of obstacles faced by stakeholders such as manual checking as well as the large plantation areas requiring a lot of time, a large budget, and insufficient human resources. Monitoring palm oil health using UAV/Drone with GIS analysis provides several advantages over manual methods that can map large coverage in a faster and more efficient time (Hassanein & El-Sheimy, 2018). This is expected to increase the intensity of plant health monitoring, especially to provide a positive response to targeted treatments that have an impact on increasing palm oil production. Therefore, this research aims to demonstrate the role of UAV/Drone technology in monitoring and detecting palm oil health that can be used by stakeholders easily, quickly, cheaply, and extensively.

2. Data and Methods

2.1. Study Area and Research Methods

This research was conducted in Argomulyo Village, Sepaku District, Penajam Paser Utara Regency, East Kalimantan Province, which has abundant palm oil plantations. Palm oil health mapping is needed in plantation management to increase yield productivity (Pribadi et al., 2023). The research was conducted on an area of ±811 ha using the coordinate system of transverse mercator (TM) 3° zone 50.2 at the location of smallholders.

The research was conducted by taking aerial photographs of palm oil plantation areas and advanced GIS analysis. The research was conducted using mixed methods based on the results of spatial analysis of aerial photographs and the benefits of UAV/Drone technology in the plantation sector. The research procedure involved GCP installation, aerial photography, and GIS analysis using the VARI method to determine the health of the palm oil (Chaudhry et al., 2021; Valluvan et al., 2023). To support information about the low use of UAV/Drone in palm oil health surveillance, a descriptive qualitative study was carried out by conducting in-depth interviews by purposive sampling to smallholders, private estates, and employees of the National Land Agency who work in Province Offices and Regency Offices in several Indonesian provinces.

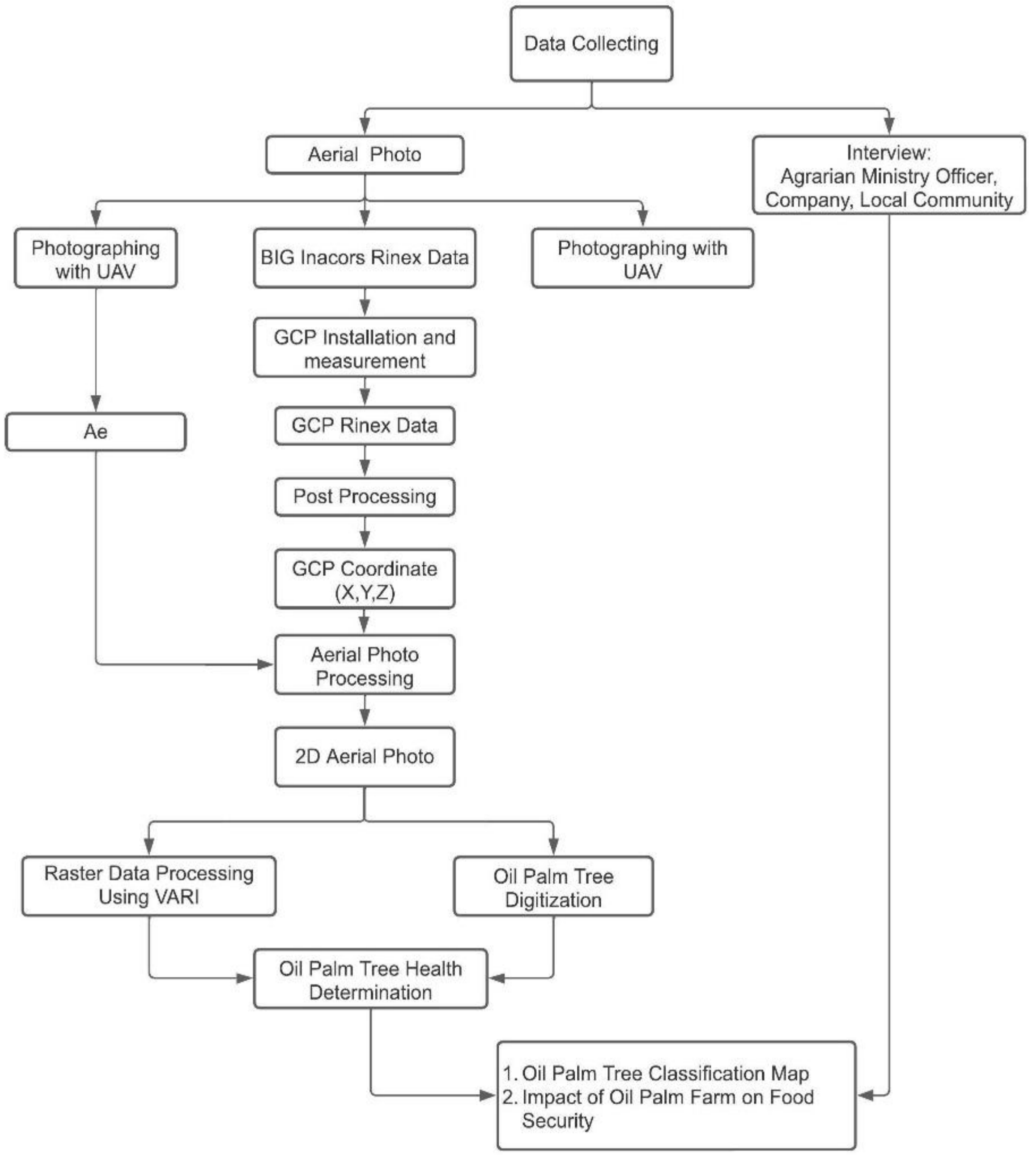

Figure 1. Research Flow Chart

2.2. Aerial Photography Mapping Using UAV/Drone

Aerial photography is divided into three stages, namely preparation, execution, and processing (Ngadiman et al., 2018). Aerial photography preparation begins with the installation of GCP at the AOI as coordinate points at the mapping location (premark) in the form of easily recognizable natural objects or artificial objects in the form of contrasting colored crosses to be visible during aerial photography processing (Kurczyński et al., 2019; Martínez-Carricondo et al., 2018). The next process is GCP data measurement by installing a GNSS receiver on top of the premark to capture and record horizontal (x,y) and vertical (z) coordinate data statically to get more accurate results (Ogutcu et al., 2023; Padró et al., 2019). This research also requires coordinating reference data as material for processing aerial photographs (Choi et al., 2022) to obtain accurate results, namely RINEX Ground Control Point (GCP) data in the mapping area and InaCors data from Geospatial Information Agency (BIG) Balikpapan Station. The implementation stage is carried out through mapping using a UAV/Drone based on the flight path plan that has been made with Litchi software (Christiansen et al., 2017). At the end is the data processing stage to produce aerial photos using Agisoft Metashape Professional software. Data processing is done by combining all photos through the stages, namely adding a photo, aligning the photo, GCP input, building dense cloud, building mesh, building texture, building dem, building ortho mosaic, and exporting (Muddarisna et al., 2018).

2.3. Aerial Photography Accuracy

Map accuracy shows the disparity between the coordinates of the points displayed on the map with the actual position to meet the standards through a calculation process that can be accounted for, accurate, reliable, and trusted (Badan Informasi Geospasial, 2018). Aerial photographs that have been processed need to know the Root Mean Square Error (RMSE) value by comparing the GCP coordinate value of the processing results with the GCP coordinate value that appears on aerial photographs to get a CE90 value that serves to determine the quality of aerial photographs (Ihsan et al., 2019). Map accuracy according to the Geospatial Information Agency is obtained from the calculation as follows:

$$CE90 = 1.5175 \times RMSEr \qquad (1)$$

RMSEr: Root Mean Square Error at horizontal x and y position

Table 1 shows the CE90 scale classification. The smaller the value, the better the quality of the aerial photo, which is aligned with the scale value.

Table 1. Classification of Base Map Thoroughness

No	**Scale**	**Contour (m)**	**Map Accuracy**					
			First Class		**Second Class**		**Third Class**	
			Horizontal (CE90 in m)	**Vertical (LE90 in m)**	**Horizontal (CE90 in m)**	**Vertical (LE90 in m)**	**Horizontal (CE90 in m)**	**Vertical (LE90 in m)**
1	1:25,000	10	7.5	5	15	7.5	22.5	10
2	1:10,000	4	3	2	6	3	9.0	4
3	1:5,000	2	1.5	1	3	1.5	4.5	2
4	1:2,500	1	0.75	0.5	1.5	0.75	2.3	1
5	1:1,000	0.4	0.3	0.2	0.6	0.3	0.9	0.4

Source: Badan Informasi Geospasial, 2018

2.4. Visible Atmospherically Resistant Index (VARI)

The result of aerial photography needs to be processed by the palm oil vegetation index to determine its health level. The vegetation index of greenness value is obtained by processing the camera sensor signal against the visible light spectrum in the vegetation canopy (Dehkordi et al., 2020; Eng et al., 2019). The healthy plant contains chlorophyll which reflects more green spectral light and absorbs red and blue spectral light (Luo et al., 2022; Salata et al., 2020). (Kaufman & Tanré, 1992) introduced the ARVI index to reduce atmospheric effects which was later improved by (Gitelson et al., 2002) by proposing the VARI method (Wijayanto et al., 2020). VARI is obtained by the following calculation (Gitelson et al., 2002; Mokarram et al., 2016; Saddik et al., 2022; Viera-Torres et al., 2020):

$$VARI = (Green - Red)/(Green + Red - Blue) \qquad (2)$$

Green = Green band
Red = Red band

Blue = Blue band

The calculation of the VARI method uses the raster function of band arithmetic in ArcGIS Pro software. This is very good at providing the value of object reflections received by the UAV/Drone camera sensor by displaying the visible electromagnetic spectrum, namely red, green, and blue or RGB (Nguyen et al., 2021). Processing the VARI method by entering the red spectrum in band 1, green in band 2, and blue in band 3.

2.5. Data Processing for Palm Oil Health Determination

Determining the health of palm oil needs to be done on each tree to get the correct value as information to determine the health classification (Wang et al., 2019). To identify palm oil carefully, digitization was carried out (Budiman et al., 2022) in the form of shapefile (shp) points using ArcGIS Pro software. Point digitization was carried out in the center of the plant then the point that resulted was converted into a polygon through a circular buffer process with a diameter of ±3 m. The determination of diameter is based on the estimation of the average size of palm oil branches seen in aerial photographs.

The final process in health determination is to find the VARI vector value per palm oil plant using zonal statistics as table by combining VARI raster data and digitized shp (Zhang et al., 2015). Zonal statistics as table with the mean statistic type will calculate the average VARI value for each palm oil digitization then the results are presented in a table. The table is then merged back with palm oil trees digitization spatial data through join fields (combining data based on the same ID between table data and digitized shp data). Furthermore, palm oil that already has VARI values is classified using natural breaks (jenks) by dividing the number of pixels equally for all areas to determine the number of classes and intervals (Zongfan et al., 2022).

3. Result and Discussion

3.1. GCP Observation

Argomulyo village did not find any technical base point or benchmark (BM) which became the base station, so the binding was done to InaCors BIG Balikpapan Station with coordinates 1° 15' 22'' N, 116° 50' 22'' E, 75 m based on SRGI 2013 reference system. The GNSS receiver used is CHCNav with a data recording time of 90-120 minutes, which is due to the location of the base station with GCPs very far away. GCP data processing uses the post-processing method with Trimble Busines Center (TBC) software. Post-processing calculations use the trilateration net method, so that the GCP coordinates correct each other's data quality with fellow GCP points and the base station. All GCPs are evenly distributed in the AOI and installed in locations that are not covered by buildings and plants, as well as are easily accessible by roads.

The determination of CE90 is based on the United States National Map Accuracy Standards (US NMAS) with the formula CE90=1.5175 x RMSEr. The RMSEr value is obtained by summing the RMSEx and RMSEy values divided by two. The RMSEx value is 0.071 m and RMSEy is 0.044 m which is obtained by the square root of the difference between aerial photography coordinates and actual coordinates divided by the number of GCP points. The results of the calculation of planimetric coordinates obtained a CE90 value of 0.088 m which means that the horizontal accuracy test is included in the scale map category of 1: 1,000, namely first class order (good) with a maximum accuracy of 0.3 m, so that this aerial photo can be used for large-scale mapping such as palm oil modeling (Badan Informasi Geospasial, 2018).

Table 2. Aerial Photography Horizontal Accuracy Test

Code	X GCP	Y GCP	X Photo	Y Photo	Difference X	Difference Y	RMSE X	RMSE Y	CE90
GCP01	348,888.951	1,397,732.560	348,888.950	1,397,732.558	0.001	0.002			
GCP02	347,792.824	1,397,529.236	347,792.689	1,397,529.256	0.135	-0.020			
GCP03	346,704.864	1,396,646.432	346,704.858	1,396,646.430	0.006	0.002			
GCP04	348,577.562	1,396,093.847	348,577.545	1,396,093.844	0.017	0.003			
GCP05	346,406.089	1,396,130.692	346,406.212	1,396,130.716	-0.123	-0.024	0.071	0.044	0.088
GCP06	345,753.153	1,395,486.653	345,753.209	1,395,486.757	-0.056	-0.104			
GCP07	347,933.465	1,395,121.478	347,933.484	1,395,121.476	-0.020	0.002			
GCP08	347,413.409	1,394,742.946	347,413.416	1,394,742.948	-0.007	-0.002			
GCP09	346,211.159	1,394,690.683	346,211.252	1,394,690,761	-0.093	-0.078			

Source: Analysis Result, 2024

3.2. Orthophotos and VARI Processing

The results of processing aerial photos using DEM data as photo reconstruction to produce the most optimal orthophoto compared to other data. The resolution of aerial photos is 5.12 cm/pixel, much higher than DEM due to the merging of aerial photos from the acquisition results. Digitization of palm oils is necessary to provide precise positioning for health determination per plant. The AOI is ±20 ha of the total aerial photo area of ±811 ha because it already represents the sample area shown in Figure 2 (left). The identification results are 2,167 palm oil plants that are evenly distributed and the empty areas are shrubs, other vegetation outside palm oil, and access roads in each palm oil block. VARI results show values with a range of -8 to 19. Figure 2 (right) shows the low nominal value in green, the higher value in yellow, and the highest value in red. The smaller even minus value indicates worse health areas seen in the aerial photo. It can be seen in Figure 2 (right) that shrubs, soil, and roads are marked in green areas. The yellow areas show vegetation with unhealthy leaf canopies and the red areas show vegetation with healthy canopies. It is quite clear that the red areas are in each palm oil canopy close to the trunk. This is due to the richness of nutrients in these areas. The values in Figure 2 (right) are not the final VARI processing values for vegetation health, additional analysis needs to be carried out for each pixel on the palm oil areas with the VARI raster data.

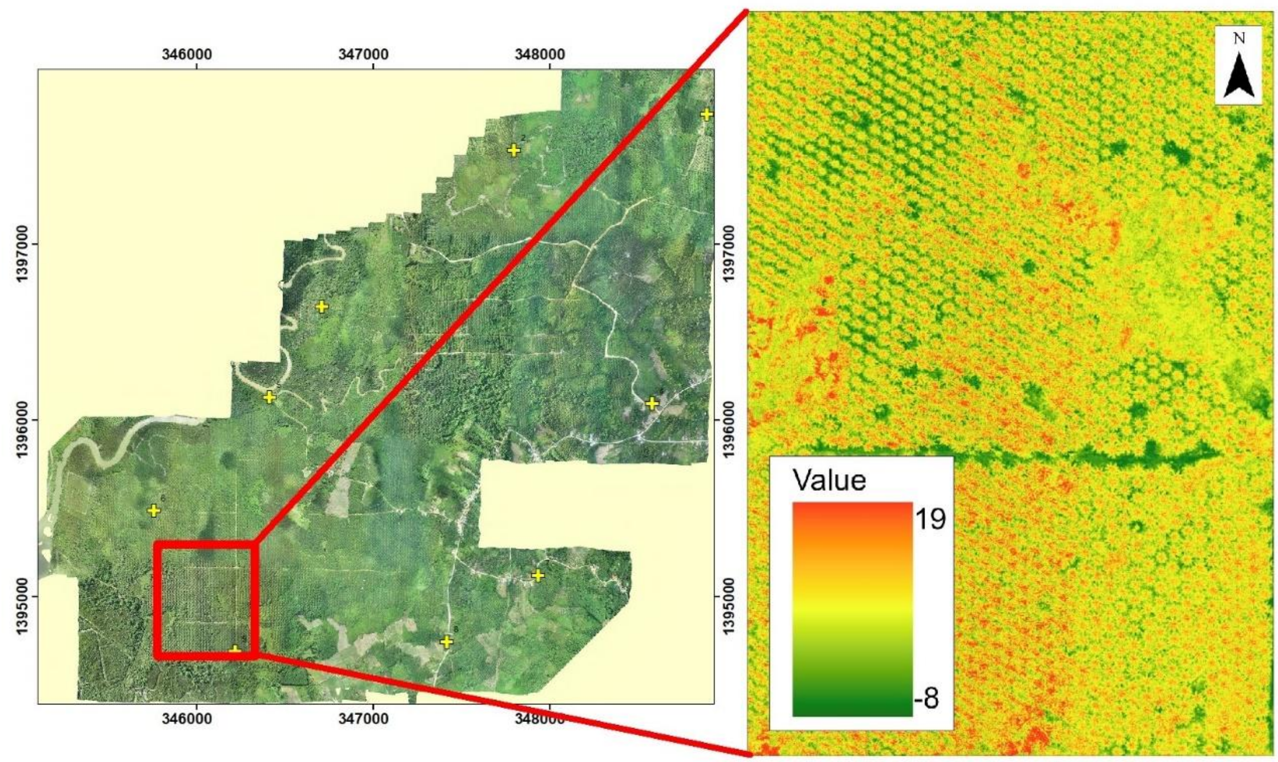

Figure 2. Aerial Photo (left) and VARI Values (right)
Source: Analysis Result, 2024

3.3. Palm Oil Health

There are 4 classifications in determining health using natural breaks (jenks) including the value of 0.048385-0.178361 given a red color for very unhealthy palm oil, the value of 0.178362-0.210414 given an orange color for unhealthy palm oil, the value of 0.210415-0.243341 given a purple color for healthy palm oil, and the value of 0.243342-0.370319 given a blue color for very healthy palm oil. These results were obtained by further spatial analysis between the VARI values and palm oil areas with pixel value equalization. Figure 3 shows in detail that the health value against the number of plants. The smallest value of 0.048385 was identified in 1 plant, the largest value of 0.370319 was identified in 3 plants, and the average value of 0.21143 was 446 plants.

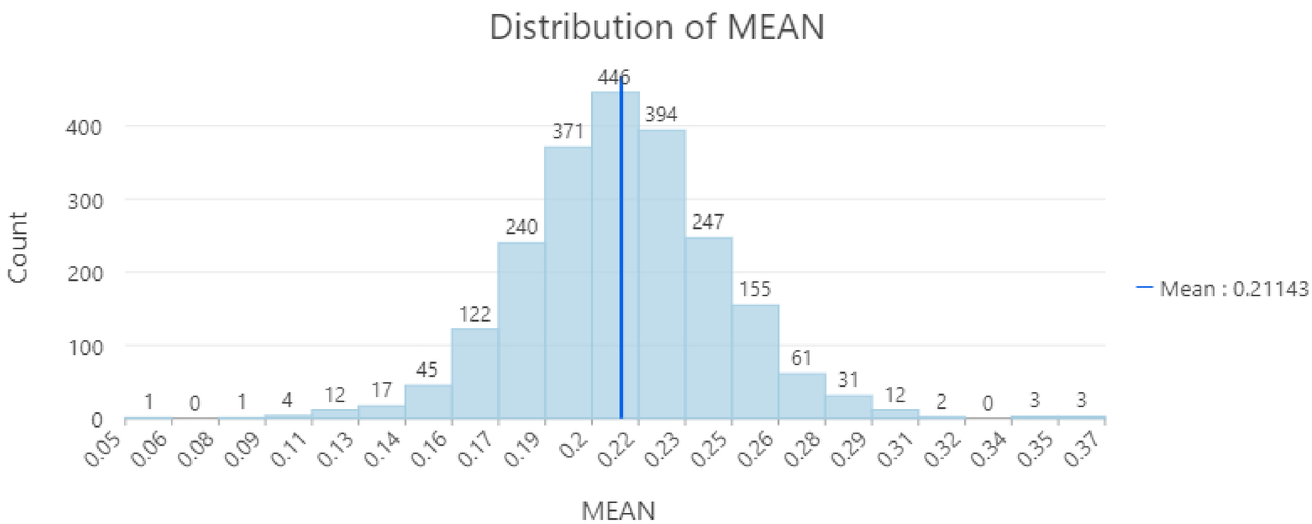

Figure 3. Histogram of VARI Values for Palm Oil Health
Source: Analysis Result, 2024

Based on the classification, 303 palm oils were found to be very unhealthy (14%) and require extra care. Very unhealthy palm oils dominate in the upper block of the left part, it appears on the map that the area is not penetrated by other roads which indicates that monitoring is rarely carried out. The distribution of very unhealthy palm oils in certain spots indicates the factor of human error that forgets maintenance due to the large number of palm oil plants and some locations that are difficult to reach. Unhealthy palm oils dominate the upper block area with 750 plants (34.61%) that are evenly distributed. In addition, in the middle block area which is more difficult to reach, there is no visible road access. Furthermore, the healthy palm oils category is 792 plants (36.54%) spread across the upper and lower blocks. The upper block shows healthy palm oils on the south side, meaning that road access is better even though it does not penetrate other blocks. This is corroborated by the lower block which is dominated by the healthy palm oils category. There are 322 plants categorized as very healthy palm oils (14.85%) spread across the lower block and upper block on the south side. It can be seen on the map that the ease of road access on the north and east side of the lower block is a supporting factor and the intensity of maintenance is dominated in the lower block where very unhealthy and unhealthy palm oils are rarely seen.

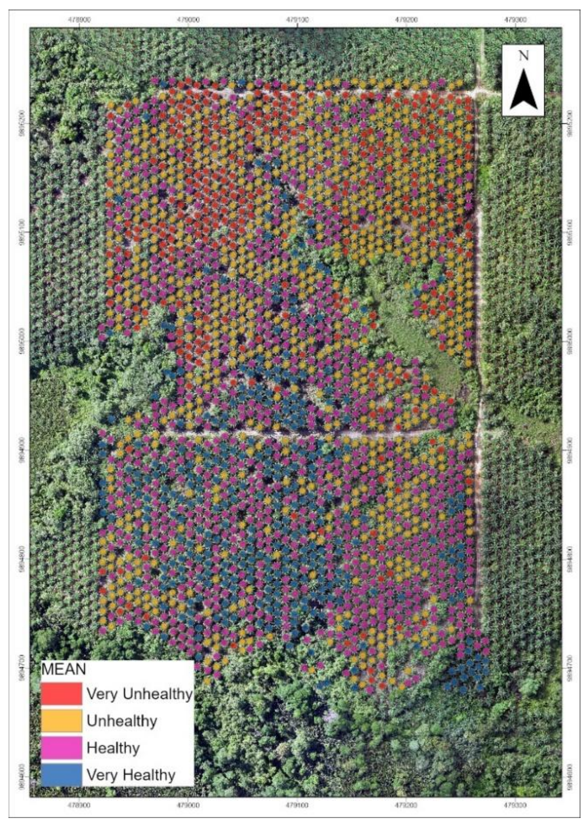

Figure 4. Palm oil Health Classification Map
Source: Analysis Result, 2024

3.4. Food Availability with Palm Oil Plantations on Food Security

In this post-pandemic period, innovation is needed to maintain the balance of demand and availability (Sridhar et al., 2022; Suma, 2021). State policies and instruments must lead to the fulfillment of urgent needs, namely the food needs of the people (Ammann et al., 2023). In addition, the fulfillment of needs is still required to pay attention to the environmental context and biodiversity in a comprehensive manner (Galeana-Pizaña et al., 2018). Sustainability is the idea of thinking about the future that connects the balance of the environment, social conditions, and the economy, along with development that aims to improve the quality of life without depleting resources (Mensah, 2019). Pillars of sustainability: Economic Sustainability means the fulfillment of consumption without sacrificing the needs of the future, the assumption of an abundant supply of natural resources does not mean that it is placed in an inappropriate market economy (Tranggono et al., 2019). Production, distribution, and consumption processes are known to be increasingly transboundary due to technological effectiveness and efficiency. Various regions are trying to increase food self-sufficiency and reduce poverty through improved food security policies while preserving the environment (Cattivelli, 2022; Galeana-Pizaña et al., 2018).

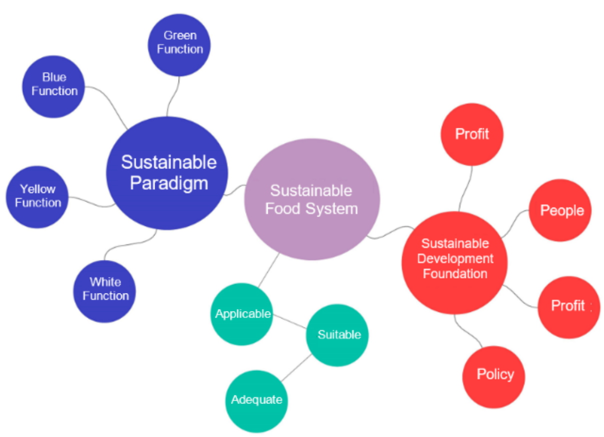

Figure 5. The Relationship Net between Sustainable Paradigm and Sustainable Development Foundation
Source: PASPI, 2021

Figure 5 is the concept of a Sustainable Food System which has a combination of the Sustainable Paradigm and Sustainable Development Foundation theories (PASPI, 2021). The Sustainable Paradigm alludes to the multifunctional theory of agriculture discussed at the 1992 Rio Earth Summit including the green function (nature and biodiversity management); the blue function (water management); the yellow function (community sociology); and the white function (food security and safety). This theory conceptualizes multifunctional build-in agriculture in which farms not only provide food products but also provide soil and environmental conservation landscapes (green-blue), which contribute to human socio-economic survival (yellow-white) (PASPI, 2021). The Sustainable Development Foundation according to the World Bank relates to the sustainable paradigm based on the 4P concept including profit (white function), people (yellow function), planet (green and blue function), and policy (World Bank, 2012). The combined implementation of the two theories such as the resilience and availability of vegetable oil (white function), can affect society (4P).

In the post-pandemic period, the price of Crude Palm Oil (CPO) experienced sharp fluctuations due to intense competition for palm oil prices. (Cheah et al., 2023). Furthermore, Supply Chain Management (SCM) is an integrated production process with distribution flows to consumers (Nchanji & Lutomia, 2021). According to analyst Michael Filbery (Phillip Securities Indonesia), the SCM constraints on palm oil products were due to the negative impact of the pandemic which caused a drastic decline in demand and a halt in CPO consumption by the tourism sector and the restaurant industry (people). Furthermore, from November 2021 to May 2022, there was a sharp correction in CPO (5%) after a large demand from palm oil importing countries which increased by 55% from the previous year (Kementerian Perdagangan Republik Indonesia, 2021). At the end of the second quarter of 2022, CPO prices fell sharply by 40% due to the COVID policy, illegal exports, and logistics access constraints (Syahfitri et al., 2022). Over time, internal causes of palm oil price fluctuations include palm oil hoarding, labor shortages, bad weather, as well as quarantine and mobility restrictions (Aryani et al., 2022). This caused the demand for CPO production to double and had a domino effect on the increase in palm oil prices (profit) (Dandi Bahtiar & Faraitody, 2022; Nafisah & Amanta, 2022).

Vegetable cooking oil sources in Indonesia have prices that are directly correlated with the international CPO market (Nafisah & Amanta, 2022). In 2021, CPO prices rose by 36%, which had a domino effect on the increase in cooking oil prices from the end of October 2021 to June 2022. People's behavior regarding variations in choosing, buying, using, and discarding the goods and services they have used affects the fulfillment of consumer wants or needs (Ernah & Tanaem, 2021). At the beginning of the pandemic, people reduced spending and focused on prioritizing their needs, but after the recovery of economic activity in mid-2021 there was an increase in purchasing power. Of course, this has an impact on the amount of domestic vegetable oil consumption which is threatened due to competition to fulfill life's needs. Indications of a surge in CPO prices are feared to have an impact on people who do not have sufficient access, ability, and even availability to purchase palm oil (white and yellow function).

Food security has four variables that must be fulfilled, namely food availability, accessibility, utilization, and stability (Kamenya et al., 2022). Food availability according to Law No. 18/2012 is a condition of availability of food production, food reserves, and import activities to meet domestic needs (Pemerintah Pusat, 2012). Food accessibility is defined as the ability of households to obtain food. Food utilization is the ability of individuals to absorb nutrients from the body. Food security is when people have physical and economic access at all times to sufficient, safe, and nutritious food to fulfill their needs for a healthy life (Hervas, 2021; Suma, 2021). In practice, the development paradigm with the food strategy will depend on the current market conditions (Hervas, 2021). The effect of palm oil prices is felt directly by the community given the impact of fluctuations in buying and selling prices on the market.

3.5. Food Availability with Palm Oil Plantations towards Smart Agriculture

The development of the needs and desires of humanity requires various technological solutions that are fast and precise to fulfill their needs. The use of technology for agriculture can increase production power and efficiency of product quality results. Furthermore, it is expected that there will be an increase in the standard of living of the parties involved in agriculture 4.0 activities (Klerkx et al., 2019; Sudaryanto et al., 2022). Agriculture 4.0 initiated the merger of digital technology and the food production chain involving pentahelix collaboration (Kheyfets & Chernova, 2019). Studies on the use of agricultural technologies emphasize cost savings as well as taking advantage of the comprehensive implementation of such technologies (Akhter & Sofi, 2022). A study outlines the perceived benefits of integrating technology with farming in production and monitoring activities in the United States. A sample of 837 farmers with a wide variety of crops and various regions stated that 25% utilize UAV/Drone in monitoring their plantations. It was also found that 88% of business respondents agreed that the right farming technology is a contributor to their financial profitability. Furthermore, 51% of the respondents agreed that the use of agricultural technology can save their farming budget and the remaining 49% felt that the technology increases yield and harvest efficiency (Thompson et al., 2019).

According to (Suma, 2021) and (Sisinni et al., 2018), the role of IOT in the smart agriculture agenda is to control irrigation, soil moisture, plant growth, and production management according to smart agriculture. IOT means internet-connected equipment containing sensors, transducers, and network connections to exchange data (Sanjeevi et al., 2020), even now able to identify health in plants from their leaf canopy. Indonesia is known as the world's largest palm oil exporter with a productivity of 43.5 million tons (Cisneros et al., 2021) with a total plantation area of 14,456,461 hectares (Kementerian Pertanian, 2022). The palm oil commodity contributes to the country's foreign exchange, produces vegetable oil for food, and can produce biodiesel energy that is more environmentally friendly (Ayompe et al., 2021). The Roundtable on Sustainable Palm Oil (RSPO) work plan is one of the strategies to regulate governance as well as equity and social relations in the agricultural commodity chain, to create sustainable yield management by applying inclusive concepts for the community (Johnson, 2022) by actualizing various innovations in agricultural technology (Córdoba et al., 2022).

Palm oil plantations in Indonesia are suitable to use the concept of Large Scale Precision Agriculture (PA) and Smart Agriculture. Precision Agriculture is the disciplined character of data collection, memory, and processing from various digital sources with a specific purpose (Hrustek, 2020). Smart Agriculture is the implementation of integrated software, hardware, and brainware to process raw data into agricultural information (Eastwood et al., 2017; Klerkx et al., 2019; Qubaa et al., 2021). The latest concept in the palm oil sector is Smart Farming Based Digital which implements the Precision Agriculture Platform for Palm Oil (Precipalm) and Electronic Plantation Control System (ePCS). Precipalm moves to support the transformation of Information and Communication Technology (ICT) by Agriculture 4.0 (Aslan et al., 2022) whose main concept is the development of sustainable agro-industry through cooperative relationships involving communities and organizations, as well as state and private business entities that remain within the legality of policies and regulations. Such cooperation includes the application of modern blockchain in the production-distribution of CPO and even joint efforts in the procurement of agri-drone for land mapping, monitoring of palm oil plants, sprayer-drone, and soil sensor management (Bharambe et al., 2020).

The manifestation of these various aspects requires comprehensive plantation production management. Through in-depth interviews with palm oil plantation businesses and the National Land Agency (the agency that issues Plantation Business Use Rights), information was obtained on the utilization of UAV/Drone technology for monitoring palm oil health. Based on the results of interviews conducted with 15 employees of the National Land Agency who work in Province Offices and Regency Offices from Kalimantan, Riau, Jambi, Sulawesi, and Papua that ± 45 palm oil companies visited and found only one company that uses UAV/Drone as a means of monitoring the quality of palm oil health. The use of UAV/Drone so far has only been for land mapping and planting points. Interviews conducted with 2 smallholders and 5 private estates found various advantages and disadvantages in trying to manage palm oil plantations. Shown in Table 3 as the results of in-depth interviews with palm oil smallholders and private estates.

Table 3. Stakeholders Interview

Factor	Smallholders	Private Estates
Human Resources	Human resources are sufficient due to the involvement of landowners who manage their plantations. However, there is often a shortage of workforce when harvesting and weeding are carried out simultaneously in several palm oil plantations.	Human resources who master GIS knowledge are insufficient due to the large area of palm oil plantations.
Technology	Manual work and daily habits using makeshift tools and labor.	Most of the work has been taken over by technological tools, as evidenced by the fact that four companies use UAV/Drone for land mapping, but very rarely for palm oil health monitoring.
Funding Availability	Not having the financial resources to develop their farming methods from manual to modern due to the focus on "enough for household needs".	Have plenty of funds to develop their farming systems, as evidenced by the use of UAV/Drone and various technological tools in the planting, maintenance, and harvesting processes.
Time	Flexible in conducting maintenance, but there is often a delay in harvest time due to labor shortage.	Carried out periodically by taking several samples and this is an obstacle to the proportion of samples and the total plantation area is not balanced.
Area	Only 2-5 hectares on average.	Over 500 to 20,000 hectares.

Source: Analysis Result, 2024

The nature of plantation mechanization can be useful in increasing mechanical labor, reducing defects and failures, increasing the quality of crops, supporting the provision of facilities, increasing labor productivity, and efforts to transform traditional (manual) plantations into more modern ones to determine the best plan for improving the palm oil health surveillance system (Aldillah, 2019; Wulandari & Wiranata, 2022). The results of the interviews show that the mechanization of plantation production in the form of the use of UAV/Drone is still not widely used to monitor smallholders and private estates. The study conducted (Hassan et al., 2022) recommended AI cognitive algorithms to interpret and react to crop conditions with accuracy, accessibility, and easily monitored processing. However, according to (Tayade et al., 2022) AI technology is still minimally developed and requires expensive equipment to obtain quality data and information. By the nature of plantation mechanization, the use of UAV/Drone can be the most appropriate means for business actors in all strata to monitor their plantations. The concept of ePCS and Precipalm can be adopted to replace the entire conventional recording process with digital and the condition of palm oil plants can be known in real time. It can involve pentahelix collaboration in the supply blockchain corridor to share costs in production, maintenance, and monitoring.

4. Conclusion

Monitoring palm oil health in the post-pandemic era is necessary to maintain food availability, stability, and accessibility. Food availability and security can be met through the Sustainable Food System, a concept to meet food needs while taking into account environmental factors for future needs, which is composed of components of natural management (green), water (blue), social society (yellow), and food security (white), as well as government policies (policy). The pandemic period that occurred resulted in the instability of palm oil production and consumption levels, which adversely affected the inconsistency of the sector.

The application of Smart Agriculture is the implementation of software, hardware, and brainware that are integrated in obtaining agricultural information to increase the production power and efficiency of palm oil can reduce the risk of failure of the Sustainable Food System in the future. Determination of palm oil health is carried out by GIS analysis using aerial photographs with the VARI vegetation index method on 2,167 samples in the Argomulyo Village community plantation with classifications including 14% very unhealthy, 34.61% unhealthy, 36.54% medium/healthy, and 14.85% very healthy. Unhealthy and very unhealthy palm oils require further comprehensive handling to prevent further spread and damage which ultimately affects the level of food availability and security.

The main purpose of utilizing GIS in terms of palm oil health control is to expand access to data and information for stakeholders by utilizing technology. Smallholders and private estates can implement the method of determining palm oil health using aerial photography with VARI analysis. This is important to do to increase the productivity of plantations. The role of the government is important in encouraging stakeholders to actualize this method through the formulation of regulations or policies related to the use and legality of UAV/Drone. Of course, pentahelix collaboration plays a major part in the development of palm oil plantation activities and even other crop commodities to increase the efficiency and effectiveness of agricultural land for sustainable food.

5. Acknowledgments

The author would like to thank the Regional Office of National Land Agency East Kalimantan Province and especially Mohamad Gugus Perdana and Noor Santy Haqim as Section Heads in Measurement and Mapping for providing the opportunity to take aerial photographs in Sepaku Village so that the author can develop these results in the processing of in-depth palm oil health analysis.

6. References

Akhter, R., & Sofi, S. A. (2022). Precision agriculture using IoT data analytics and machine learning. *Journal of King Saud University - Computer and Information Sciences*, *34*(8), 5602–5618. https://doi.org/10.1016/J.JKSUCI.2021.05.013

Aldillah, R. P. S. E. dan K. P. Jln. T. P. No. 3B, B. 16111, J. B. I. (2019). Kinerja Pemanfaatan Mekanisasi Pertanian dan Implikasinya dalam Upaya Percepatan Produksi Pangan di Indonesia. *Forum Penelitian Agro Ekonomi*, *34*(2), 163. https://doi.org/10.21082/FAE.V34N2.2016.163-171

Amirruddin, A. D., Muharam, F. M., Ismail, M. H., Ismail, M. F., Tan, N. P., & Karam, D. S. (2020). Hyperspectral remote sensing for assessment of chlorophyll sufficiency levels in mature palm oil (Elaeis guineensis) based on frond numbers: Analysis of decision tree and random forest. *Computers and Electronics in Agriculture*, *169*, 105221. https://doi.org/10.1016/J.COMPAG.2020.105221

Ammann, J., Arbenz, A., Mack, G., Nemecek, T., & El Benni, N. (2023). A review on policy instruments for sustainable food consumption. *Sustainable Production and Consumption*, *36*, 338–353. https://doi.org/10.1016/J.SPC.2023.01.012

Andaru, R., & Santosa, P. B. (2017). Analisis Spasial Bencana Longsor Bukit Telogolele Kabupaten Banjarnegara Menggunakan Data Foto Udara UAV. *Jurnal Nasional Teknologi Terapan (JNTT), 1(1), 77*. https://doi.org/10.22146/jntt.34089

Andaru, R and Santosa, P. B. (2017). Analisis Spasial Bencana Longsor Menggunakan Data Foto Udara UAV*. Jurnal Dialog dan Penanggulangan Bencana,* 8(2), 142-150. https://jdpb.bnpb.go.id/index.php/jurnal/article/view/124/124

Andaru, R., Aditya, T., Cahyono, B. K., Santosa, P. B., Yulaikhah, Swastika, S. P. (2024). Automatic DTM and Building Footprint Extraction from Imageries and Point Clouds in Indonesia's Land Registration Drone Survey: A Roadmap Towards Reconstruction of LOD1 3D building model. *12th International FIG Land Administration Domain Model & 3D Land Administration Workshop*, 24-26 September 2024, Kuching, Malaysia. https://www.gdmc.nl/3DCadastres/workshop2024/programme/3DLA2024_paper_D.pdf

Supriadi, A., & Oswari, T. (2020). Analysis of Geographical Information System (GIS) design aplication in the Fire Department of Depok City. *Technium Social Sciences Journal*, *8*, 1–7. https://doi.org/10.47577/TSSJ.V8I1.181

Aryani, I., Naibaho, W. A., & Aisyah, S. (2022). *Analisis Kendala Rantai Pasok Kelapa Sawit terhadap Kenaikan Harga Minyak Goreng: Studi Kasus PTPN II Batang Kuis Medan*. Jurnal Ilmu Komputer, Ekonomi Dan Manajemen (JIKEM). https://ummaspul.e-journal.id/JKM/article/view/3775/1344

Aslan, M. F., Durdu, A., Sabanci, K., Ropelewska, E., & Gültekin, S. S. (2022). A Comprehensive Survey of the Recent Studies with UAV for Precision Agriculture in Open Fields and Greenhouses. *Applied Sciences 2022, Vol. 12, Page 1047*, *12*(3), 1047. https://doi.org/10.3390/APP12031047

Ayompe, L. M., Schaafsma, M., & Egoh, B. N. (2021). Towards sustainable palm oil production: The positive and negative impacts on ecosystem services and human wellbeing. *Journal of Cleaner Production*, *278*, 123914. https://doi.org/10.1016/J.JCLEPRO.2020.123914

Badan Informasi Geospasial. (2018). *Peraturan Badan Informasi Geospasial Nomor 6 Tahun 2018*. Badan Informasi Geospasial. https://peraturanpedia.id/peraturan-badan-informasi-geospasial-nomor-6-tahun-2018/

Ballesteros, R., Moreno, M. A., Barroso, F., González-gómez, L., & Ortega, J. F. (2021). Assessment of Maize Growth and Development with High- and Medium-Resolution Remote Sensing Products. *Agronomy 2021, Vol. 11, Page*

940, *11*(5), 940. https://doi.org/10.3390/AGRONOMY11050940
Barzin, R., Pathak, R., Lotfi, H., Varco, J., & Bora, G. C. (2020). Use of UAS Multispectral Imagery at Different Physiological Stages for Yield Prediction and Input Resource Optimization in Corn. *Remote Sensing 2020, Vol. 12, Page 2392*, *12*(15), 2392. https://doi.org/10.3390/RS12152392
Bharambe, Y., Singh, D., & Binsale, V. (2020). Design and Development of Agricultural Drone for Plant Health Analysis. *International Research Journal of Innovations in Engineering and Technology (IRJIET)*, *4*(8), 6–11. https://doi.org/10.47001/IRJIET/2020.408002
Budiman, R., Seminar, K. B., & Sudrajat. (2022). The estimation of nutrient content using multispectral image analysis in palm oil (Elaeis guineensis Jacq). *IOP Conference Series: Earth and Environmental Science*, *974*(1), 012062. https://doi.org/10.1088/1755-1315/974/1/012062
Cattivelli, V. (2022). The contribution of urban garden cultivation to food self-sufficiency in areas at risk of food desertification during the Covid-19 pandemic. *Land Use Policy*, *120*, 106215. https://doi.org/10.1016/J.LANDUSEPOL.2022.106215
Chaudhry, M. H., Ahmad, A., Gulzar, Q., Farid, M. S., Shahabi, H., & Al-Ansari, N. (2021). Assessment of DSM Based on Radiometric Transformation of UAV Data. *Sensors 2021, Vol. 21, Page 1649*, *21*(5), 1649. https://doi.org/10.3390/S21051649
Cheah, W. Y., Siti-Dina, R. P., Leng, S. T. K., Er, A. C., & Show, P. L. (2023). Circular bioeconomy in palm oil industry: Current practices and future perspectives. *Environmental Technology & Innovation*, *30*, 103050. https://doi.org/10.1016/J.ETI.2023.103050
Choi, Y., Park, S., & Kim, S. (2022). GCP-Based Automated Fine Alignment Method for Improving the Accuracy of Coordinate Information on UAV Point Cloud Data. *Sensors 2022, Vol. 22, Page 8735*, *22*(22), 8735. https://doi.org/10.3390/S22228735
Christiansen, M. P., Laursen, M. S., Jørgensen, R. N., Skovsen, S., & Gislum, R. (2017). Designing and Testing a UAV Mapping System for Agricultural Field Surveying. *Sensors 2017, Vol. 17, Page 2703*, *17*(12), 2703. https://doi.org/10.3390/S17122703
Cisneros, E., Kis-Katos, K., & Nuryartono, N. (2021). Palm oil and the politics of deforestation in Indonesia. *Journal of Environmental Economics and Management*, *108*, 102453. https://doi.org/10.1016/J.JEEM.2021.102453
Córdoba, D., Abrams, J., & Selfa, T. (2022). Achieving Palm Oil Sustainability Under Contract: Roundtable on Sustainable Palm Oil and Family Farmers in the Brazilian Amazon. *Current Research in Environmental Sustainability*, *4*, 100160. https://doi.org/10.1016/J.CRSUST.2022.100160
Dandi Bahtiar, O. :, & Faraitody, D. (2022). Analisis Kinerja Perusahaan Dan Nilai Perusahaan Pada Perusahaan Perkebunan Kelapa Sawit Dan Hubungannya Dengan Kenaikan Harga Minyak Goreng (Studi Kasus Perusahaan Perkebunan Kelapa Sawit Yang Terdaftar Di Bursa Efek Indonesia). *AGROSCIENCE*, *12*(1), 32–49. https://jurnal.unsur.ac.id/agroscience/article/view/2192
Dehkordi, R. H., EL JARROUDI, M., Kouadio, L., Meersmans, J., & Beyer, M. (2020). Monitoring Wheat Leaf Rust and Stripe Rust in Winter Wheat Using High-Resolution UAV-Based Red-Green-Blue Imagery. *Remote Sensing 2020, Vol. 12, Page 3696*, *12*(22), 3696. https://doi.org/10.3390/RS12223696
Eastwood, C., Klerkx, L., & Nettle, R. (2017). Dynamics and distribution of public and private research and extension roles for technological innovation and diffusion: Case studies of the implementation and adaptation of precision farming technologies. *Journal of Rural Studies*, *49*, 1–12. https://doi.org/10.1016/J.JRURSTUD.2016.11.008
Eng, L. S., Ismail, R., Hashim, W., & Baharum, A. (2019). The use of VARI, GLI, And VIgreen formulas in detecting vegetation in aerial images. *International Journal of Technology*, *10*(7), 1385–1394. https://doi.org/10.14716/IJTECH.V10I7.3275
Ernah, E., & Tanaem, M. G. (2021). Perilaku Konsumen Minyak Goreng Sawit selama Masa Pandemi Covid-19 di Kota Bandung Jawa Barat. *Agritech : Jurnal Fakultas Pertanian Universitas Muhammadiyah Purwokerto*, *23*(1), 10–16. https://doi.org/10.30595/AGRITECH.V23I1.9530
Fatmayati, F., Veronika, N., & Khairiah, H. (2022). Penyuluhan Penanganan Batang Sawit Pada Kelompok Tani Sawit Maju Bersama Di Kabupaten Kampar. *Journal of Community Service in Science and Engineering (JoCSE)*, *1*(1), 9–11. https://doi.org/10.36055/jocse.v1i1.16823
Fountas, S., Espejo-Garcia, B., Kasimati, A., Mylonas, N., & Darra, N. (2020). The Future of Digital Agriculture: Technologies and Opportunities. *IT Professional*, *22*(1), 24–28. https://doi.org/10.1109/MITP.2019.2963412
Galeana-Pizaña, J. M., Couturier, S., & Monsivais-Huertero, A. (2018). Assessing food security and environmental protection in Mexico with a GIS-based Food Environmental Efficiency index. *Land Use Policy*, *76*, 442–454. https://doi.org/10.1016/J.LANDUSEPOL.2018.02.022
Gao, D., Sun, Q., Hu, B., & Zhang, S. (2020). A Framework for Agricultural Pest and Disease Monitoring Based on

Internet-of-Things and Unmanned Aerial Vehicles. *Sensors 2020, Vol. 20, Page 1487*, *20*(5), 1487. https://doi.org/10.3390/S20051487

García-Martínez, H., Flores-Magdaleno, H., Ascencio-Hernández, R., Khalil-Gardezi, A., Tijerina-Chávez, L., Mancilla-Villa, O. R., & Vázquez-Peña, M. A. (2020). Corn Grain Yield Estimation from Vegetation Indices, Canopy Cover, Plant Density, and a Neural Network Using Multispectral and RGB Images Acquired with Unmanned Aerial Vehicles. *Agriculture 2020, Vol. 10, Page 277*, *10*(7), 277. https://doi.org/10.3390/AGRICULTURE10070277

Gitelson, A. A., Kaufman, Y. J., Stark, R., & Rundquist, D. (2002). Novel algorithms for remote estimation of vegetation fraction. *Remote Sensing of Environment*, *80*(1), 76–87. https://doi.org/10.1016/S0034-4257(01)00289-9

Glover, D. (2022). Affordances and agricultural technology. *Journal of Rural Studies*, *94*, 73–82. https://doi.org/10.1016/J.JRURSTUD.2022.05.007

Hassan, S. I., Alam, M. M., Zia, M. Y. I., Rashid, M., Illahi, U., & Su'ud, M. M. (2022). Rice Crop Counting Using Aerial Imagery and GIS for the Assessment of Soil Health to Increase Crop Yield. *Sensors 2022, Vol. 22, Page 8567*, *22*(21), 8567. https://doi.org/10.3390/S22218567

Hassanein, M., & El-Sheimy, N. (2018). An Efficient Weed Detection Procedure Using Low-Cost UAV Imagery System For Precision Agriculture Applications. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(1), 181–187. https://doi.org/10.5194/ISPRS-ARCHIVES-XLII-1-181-2018

Hervas, A. (2021). Mapping palm oil-related land use change in Guatemala, 2003–2019: Implications for food security. *Land Use Policy*, *109*, 105657. https://doi.org/10.1016/J.LANDUSEPOL.2021.105657

Hrustek, L. (2020). Sustainability Driven by Agriculture through Digital Transformation. *Sustainability 2020, Vol. 12, Page 8596*, *12*(20), 8596. https://doi.org/10.3390/SU12208596

Ihsan, M., Somantri, L., Sugito, N. T., Himayah, S., & Affriani, A. R. (2019). The Comparison of Stage and Result Processing of Photogrammetric Data Based on Online Cloud Processing. *IOP Conference Series: Earth and Environmental Science*, *286*(1), 012041. https://doi.org/10.1088/1755-1315/286/1/012041

Iizuka, K., Itoh, M., Shiodera, S., Matsubara, T., Dohar, M., & Watanabe, K. (2018). Advantages of unmanned aerial vehicle (UAV) photogrammetry for landscape analysis compared with satellite data: A case study of postmining sites in Indonesia. *Cogent Geoscience*, *4*(1), 1498180. https://doi.org/10.1080/23312041.2018.1498180

Izzuddin, M. A., Hamzah, A., Nisfariza, M. N., & Idris, A. S. (2020). Analysis of multispectral imagery from unmanned aerial vehicle (UAV) using object-based image analysis for detection of ganoderma disease in palm oil. *Journal of Palm oil Research*, *32*(3), 497–508. https://doi.org/10.21894/JOPR.2020.0035

Johnson, A. (2022). The Roundtable on Sustainable Palm Oil (RSPO) and transnational hybrid governance in Ecuador's palm oil industry. *World Development*, *149*, 105710. https://doi.org/10.1016/J.WORLDDEV.2021.105710

Kamenya, M. A., Hendriks, S. L., Gandidzanwa, C., Ulimwengu, J., & Odjo, S. (2022). Public agriculture investment and food security in ECOWAS. *Food Policy*, *113*, 102349. https://doi.org/10.1016/J.FOODPOL.2022.102349

Kanning, M., Kühling, I., Trautz, D., & Jarmer, T. (2018). High-Resolution UAV-Based Hyperspectral Imagery for LAI and Chlorophyll Estimations from Wheat for Yield Prediction. *Remote Sensing 2018, Vol. 10, Page 2000*, *10*(12), 2000. https://doi.org/10.3390/RS10122000

Kaufman, Y. J., & Tanré, D. (1992). Atmospherically Resistant Vegetation Index (ARVI) for EOS-MODIS. *IEEE Transactions on Geoscience and Remote Sensing*, *30*(2), 261–270. https://doi.org/10.1109/36.134076

Kementerian Perdagangan Republik Indonesia. (2021). *Analisis Perkembangan Harga Bahan Pangan Pokok di Pasar Domestik dan Internasional*. https://bkperdag.kemendag.go.id/media_content/2021/12/file_kajian_analisis_harga_pangan_pokok_20211220091237o0bx3kapy6.pdf

Kementerian Pertanian. (2022). *Statistik Perkebunan Unggulan Nasional 2020-2022*. https://ditjenbun.pertanian.go.id/template/uploads/2022/08/STATISTIK-UNGGULAN-2020-2022.pdf

Kheyfets, B. A., & Chernova, V. Y. (2019). *Entrepreneurship And Sustainability Issues Sustainable Agriculture In Russia: Research On The Dynamics Of Innovation Activity And Labor Productivity Entrepreneurship And Sustainability Issues*. *7*(2). https://doi.org/10.9770/jesi.2019.7.2(2)

Khuzaimah, Z., Nawi, N. M., Adam, S. N., Kalantar, B., Emeka, O. J., & Ueda, N. (2022). Application and Potential of Drone Technology in Palm oil Plantation: Potential and Limitations. *Journal of Sensors*, *2022*. https://doi.org/10.1155/2022/5385505

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life*

Sciences, *90–91*, 100315. https://doi.org/10.1016/J.NJAS.2019.100315

Kurczyński, Z., Bakuła, K., Pilarska, M., & Ostrowski, W. (2019). The Problem of Using and Measurement of Identifiable Ground Control Points on High Resolution Aerial Images. *Archives of Photogrammetry, Cartography and Remote Sensing*, *31*(1), 135–144. https://doi.org/10.2478/APCRS-2019-0009

Kurkute, S. R. (2018). Drones for Smart Agriculture: A Technical Report. *International Journal for Research in Applied Science and Engineering Technology*, *6*(4), 341–346. https://doi.org/10.22214/IJRASET.2018.4061

Lova Raju, K., & Vijayaraghavan, V. (2020). IoT Technologies in Agricultural Environment: A Survey. *Wireless Personal Communications*, *113*(4), 2415–2446. https://doi.org/10.1007/S11277-020-07334-X/METRICS

Lü, G., Batty, M., Strobl, J., Lin, H., Zhu, A. X., & Chen, M. (2018). Reflections and speculations on the progress in Geographic Information Systems (GIS): a geographic perspective. *International Journal of Geographical Information Science*, *33*(2), 346–367. https://doi.org/10.1080/13658816.2018.1533136

Luo, M., Tian, Y., Zhang, S., Huang, L., Wang, H., Liu, Z., & Yang, L. (2022). Individual Tree Detection in Coal Mine Afforestation Area Based on Improved Faster RCNN in UAV RGB Images. *Remote Sensing 2022, Vol. 14, Page 5545*, *14*(21), 5545. https://doi.org/10.3390/RS14215545

Maddikunta, P. K. R., Pham, Q. V., B, P., Deepa, N., Dev, K., Gadekallu, T. R., Ruby, R., & Liyanage, M. (2022). Industry 5.0: A survey on enabling technologies and potential applications. *Journal of Industrial Information Integration*, *26*, 100257. https://doi.org/10.1016/J.JII.2021.100257

Malinee, R., Stratoulias, D., & Nuthammachot, N. (2021). Detection of Palm oil Disease in Plantations in Krabi Province, Thailand with High Spatial Resolution Satellite Imagery. *Agriculture 2021, Vol. 11, Page 251*, *11*(3), 251. https://doi.org/10.3390/AGRICULTURE11030251

Martínez-Carricondo, P., Agüera-Vega, F., Carvajal-Ramírez, F., Mesas-Carrascosa, F. J., García-Ferrer, A., & Pérez-Porras, F. J. (2018). Assessment of UAV-photogrammetric mapping accuracy based on variation of ground control points. *International Journal of Applied Earth Observation and Geoinformation*, *72*, 1–10. https://doi.org/10.1016/J.JAG.2018.05.015

Mensah, J. (2019). Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent Social Sciences*, *5*(1). https://doi.org/10.1080/23311886.2019.1653531

Mirzaliev, S. M., Homidov, H. H., Sharipov, K. A., & Kholikova, N. A. (2022). Perspectives of use of agricultural drones in Uzbekistan. *IOP Conference Series: Earth and Environmental Science*, *1045*(1), 012147. https://doi.org/10.1088/1755-1315/1045/1/012147

Mohsan, S. A. H., Khan, M. A., Noor, F., Ullah, I., & Alsharif, M. H. (2022). Towards the Unmanned Aerial Vehicles (UAV): A Comprehensive Review. *Drones 2022, Vol. 6, Page 147*, *6*(6), 147. https://doi.org/10.3390/DRONES6060147

Mokarram, M., Boloorani, A. D., & Hojati, M. (2016). *Relationship between land cover and vegetation indices. Case study: Eghlid plain, Fars Province, Iran*. European Journal of Geography. https://www.researchgate.net/publication/309066601_Relationship_between_land_cover_and_vegetation_indices_Case_study_Eghlid_plain_Fars_Province_Iran

Muda, I., Siregar, H. S., Sembiring, S. A., Ramli, Manurung, H., & Zein, Z. (2018). Economic Value of Palm Plantation in North Sumatera and Contribution to Product Domestic Regional Bruto. *IOP Conference Series: Materials Science and Engineering*, *288*(1), 012080. https://doi.org/10.1088/1757-899X/288/1/012080

Muddarisna, N., Dyah Yuniwati, E., Masruroh, H., -, al, Fu, J., Zhang, G., Wang, L., Sharan Kumar, N., Ashraf Mohamad Ismail, M., Sabahiah Abdul Sukor, N., & Cheang, W. (2018). Method for the visualization of landform by mapping using low altitude UAV application. *IOP Conference Series: Materials Science and Engineering*, *352*(1), 012032. https://doi.org/10.1088/1757-899X/352/1/012032

Nafisah, N., & Amanta, F. (2022). Produktivitas Kelapa Sawit Tetap Terbatas Seiring Melonjaknya Harga Minyak Goreng di Indonesia. *Center for Indonesian Policy Studies Repository*.

Nchanji, E. B., & Lutomia, C. K. (2021). Sustainability of the agri-food supply chain amidst the pandemic: Diversification, local input production, and consumer behavior. *Advances in Food Security and Sustainability*, *6*, 211–229. https://doi.org/10.1016/BS.AF2S.2021.07.003

Ngadiman, N., Kaamin, M., Sahat, S., Mokhtar, M., Ahmad, N. F. A., Kadir, A. A., & Razali, S. N. M. (2018). Production of orthophoto map using UAV photogrammetry: A case study in UTHM Pagoh campus. *AIP Conference Proceedings*, *2016*(1), 020112. https://doi.org/10.1063/1.5055514

Nguyen, H. T., Caceres, M. L. L., Moritake, K., Kentsch, S., Shu, H., & Diez, Y. (2021). Individual Sick Fir Tree (Abies mariesii) Identification in Insect Infested Forests by Means of UAV Images and Deep Learning. *Remote*

Sensing 2021, Vol. 13, Page 260, *13*(2), 260. https://doi.org/10.3390/RS13020260

Numbere, A. O., & Maimaitijiang, M. (2019). Mapping of Nypa Palm Invasion of Mangrove Forest Using Low-Cost and High Resolution UAV Digital Imagery in The Niger Delta, Nigeria. *Current Trends in Forest Research*, *3*(01). https://doi.org/10.29011/2638-0013.100031

Nurrizqi, F. A., Febriana, G., Arifbillah, K., & Irawan, F. (2022). Analisis Kinerja Keuangan Perusahaan Perkebunan Kelapa Sawit Saat Pandemi Covid-19. *Jurnalku*, *2*(3), 302–315. https://doi.org/10.54957/JURNALKU.V2I3.280

Ogutcu, S., Alcay, S., Ozdemir, B. N., Li, P., Zhang, Y., Konukseven, C., & Atiz, O. F. (2023). Assessing the performance of BDS-3 for multi-GNSS static and kinematic PPP-AR. *Advances in Space Research*, *71*(3), 1543–1557. https://doi.org/10.1016/J.ASR.2022.10.016

Oktarina, S. D., Nurkhoiry, R., Amalia, R., Pradiko, I., & Rahutomo, S. (2022). Dampak Ketidakpastian Covid-19, Iklim, dan Kompleksitas Lainnya Pada Industri Kelapa Sawit. *WARTA Pusat Penelitian Kelapa Sawit*, *27*(2), 70–77. https://warta.iopri.org/index.php/Warta/article/view/83

Pachayappan, M., Ganeshkumar, C., & Sugundan, N. (2020). Technological implication and its impact in agricultural sector: An IoT Based Collaboration framework. *Procedia Computer Science*, *171*, 1166–1173. https://doi.org/10.1016/J.PROCS.2020.04.125

Padró, J. C., Muñoz, F. J., Planas, J., & Pons, X. (2019). Comparison of four UAV georeferencing methods for environmental monitoring purposes focusing on the combined use with airborne and satellite remote sensing platforms. *International Journal of Applied Earth Observation and Geoinformation*, *75*, 130–140. https://doi.org/10.1016/J.JAG.2018.10.018

PASPI. (2021). Multifunctional Palm oil Plantation and Sustainable Development Goals (SDGS). *Analysis of Palm Oil Strategic Issues*, *II*, 281–288.

Pemerintah Pusat. (2012). *Undang-Undang Nomor 18 Tahun 2012 tentang Pangan*. https://peraturan.bpk.go.id/Home/Details/39100

Pollino, M., Kainz, W., Dimyati, M., Supriatna, S., Nagasawa, R., Pamungkas, D., & Pramayuda, R. (2023). A Comparison of Several UAV-Based Multispectral Imageries in Monitoring Rice Paddy (A Case Study in Paddy Fields in Tottori Prefecture, Japan). *ISPRS International Journal of Geo-Information 2023, Vol. 12, Page 36*, *12*(2), 36. https://doi.org/10.3390/IJGI12020036

Pribadi, D. O., Rustiadi, E., Syamsul Iman, L. O., Nurdin, M., Supijatno, Saad, A., Pravitasari, A. E., Mulya, S. P., & Ermyanyla, M. (2023). Mapping smallholder plantation as a key to sustainable palm oil: A deep learning approach to high-resolution satellite imagery. *Applied Geography*, *153*, 102921. https://doi.org/10.1016/J.APGEOG.2023.102921

Qubaa, A. R., Aljawwadi, T. A., Hamdoon, A. N., & Mohammed, R. M. (2021). USING UAV/Drone AND VEGETATION INDICES IN THE VISIBLE SPECTRUM TO MONITORING AGRICULTURAL LANDS. *Iraqi Journal of Agricultural Sciences*, *52*(3), 601–610. https://doi.org/10.36103/IJAS.V52I3.1349

Raj, R., Kar, S., Nandan, R., & Jagarlapudi, A. (2020). Precision Agriculture and Unmanned Aerial Vehicles (UAV). *Unmanned Aerial Vehicle: Applications in Agriculture and Environment*, 7–23. https://doi.org/10.1007/978-3-030-27157-2_2/COVER

Ren, H., Zhao, Y., Xiao, W., & Hu, Z. (2019). A review of UAV monitoring in mining areas: current status and future perspectives. *International Journal of Coal Science and Technology*, *6*(3), 320–333. https://doi.org/10.1007/S40789-019-00264-5/FIGURES/6

Roth, R. T. ;, Chen, K. ;, Scott, J. R. ;, Jung, J. ;, Yang, Y. ;, Camberato, J. J. ;, Armstrong, S. D., Roth, R. T., Chen, K., Scott, J. R., Jung, J., Yang, Y., Camberato, J. J., & Armstrong, S. D. (2023). Prediction of Cereal Rye Cover Crop Biomass and Nutrient Accumulation Using Multi-Temporal Unmanned Aerial Vehicle Based Visible-Spectrum Vegetation Indices. *Remote Sensing 2023, Vol. 15, Page 580*, *15*(3), 580. https://doi.org/10.3390/RS15030580

Saddik, A., Latif, R., El Ouardi, A., Alghamdi, M. I., & Elhoseny, M. (2022). Improving Sustainable Vegetation Indices Processing on Low-Cost Architectures. *Sustainability 2022, Vol. 14, Page 2521*, *14*(5), 2521. https://doi.org/10.3390/SU14052521

Salam, A., & Shah, S. (2019). Internet of things in smart agriculture: Enabling technologies. *IEEE 5th World Forum on Internet of Things, WF-IoT 2019 - Conference Proceedings*, 692–695. https://doi.org/10.1109/WF-IOT.2019.8767306

Salata, S., Giaimo, C., Barbieri, C. A., Ballocca, A., Scalise, F., & Pantaloni, G. (2020). The Utilization of Normalized Difference Vegetation Index to Map Habitat Quality in Turin (Italy). *Sustainability 2020, Vol. 12, Page 7751*, *12*(18), 7751. https://doi.org/10.3390/SU12187751

Sanjeevi, P., Prasanna, S., Siva Kumar, B., Gunasekaran, G., Alagiri, I., & Vijay Anand, R. (2020). Precision agriculture and farming using Internet of Things based on wireless sensor network. *Transactions on Emerging Telecommunications Technologies*, *31*(12), e3978. https://doi.org/10.1002/ETT.3978

Saroinsong, H. S., Poekoel, V. C., & Manembu, P. D. (2018). Rancang Bangun Wahana Pesawat Tanpa Awak (Fixed Wing) Berbasis Ardupilot. *Jurnal Teknik Elektro Dan Komputer*, *7*(1), 73–84. https://ejournal.unsrat.ac.id/v3/index.php/elekdankom/article/view/19195

Siregar, H. A., Yenni, Y., Setiowati, R. D., Supena, N., Suprianto, E., & Purba, A. R. (2020). Cameroon Virescens Palm oil (Elaeis guineensis) from IOPRI's Germplasm. *AGRIVITA, Journal of Agricultural Science*, *42*(2), 283–294. https://doi.org/10.17503/AGRIVITA.V0I0.2239

Sisinni, E., Saifullah, A., Han, S., Jennehag, U., & Gidlund, M. (2018). Industrial internet of things: Challenges, opportunities, and directions. *IEEE Transactions on Industrial Informatics*, *14*(11), 4724–4734. https://doi.org/10.1109/TII.2018.2852491

Sridhar, A., Balakrishnan, A., Jacob, M. M., Sillanpää, M., & Dayanandan, N. (2022). Global impact of COVID-19 on agriculture: role of sustainable agriculture and digital farming. *Environmental Science and Pollution Research*, *1*, 1–17. https://doi.org/10.1007/S11356-022-19358-W/FIGURES/8

Sudaryanto, T., Purba, H. J., Rafani, I., & Andoko, E. (2022). Promoting Smart Farming based-Digital Business Technology in the Context of Agricultural Transformation in Indonesia. *The FFTC Journal of Agricultural Policy*, *3*, 69–80.

Suma, V. (2021). Internet of Things (IoT) based Smart Agriculture in India: An Overview. *Journal of ISMAC*, *3*(1), 1–15. https://doi.org/10.36548/JISMAC.2021.1.001

Syahfitri, S., Amwa, D. R., & Aisyah, S. (2022). Peran Pemerintah Terhadap Supply Chain Management Pada Produk Minyak Goreng. *Jurnal Manajemen Akuntansi (JUMSI)*, *2*(4), 592–596. https://doi.org/10.36987/JUMSI.V2I4.3048

Tayade, R., Yoon, J., Lay, L., Khan, A. L., Yoon, Y., & Kim, Y. (2022). Utilization of Spectral Indices for High-Throughput Phenotyping. *Plants 2022, Vol. 11, Page 1712*, *11*(13), 1712. https://doi.org/10.3390/PLANTS11131712

Thompson, N. M., Bir, C., Widmar, D. A., & Mintert, J. R. (2019). Farmer Perceptions of Precision Agriculture Technology Benefits. *Journal of Agricultural and Applied Economics*, *51*(1), 142–163. https://doi.org/10.1017/AAE.2018.27

Tranggono, A., Wirman, C., Sulistiowati, A., & Avianto, T. (2019). Indonesia Sustainable Food System. *Pangan Bijak*.

Valluvan, A. B., Raj, R., Pingale, R., & Jagarlapudi, A. (2023). Canopy height estimation using drone-based RGB images. *Smart Agricultural Technology*, *4*, 100145. https://doi.org/10.1016/J.ATECH.2022.100145

Viera-Torres, M., Sinde-González, I., Gil-Docampo, M., Bravo-Yandún, V., & Toulkeridis, T. (2020). Generating the Baseline in the Early Detection of Bud Rot and Red Ring Disease in Palm oils by Geospatial Technologies. *Remote Sensing 2020, Vol. 12, Page 3229*, *12*(19), 3229. https://doi.org/10.3390/RS12193229

Wang, Y., Zhu, X., & Wu, B. (2019). Automatic detection of individual palm oil trees from UAV images using HOG features and an SVM classifier. *International Journal of Remote Sensing*, *40*(19), 7356–7370. https://doi.org/10.1080/01431161.2018.1513669

Wijayanto, A. W., Triscowati, D. W., & Marsuhandi, A. H. (2020). Maize field area detection in East Java, Indonesia: An integrated multispectral remote sensing and machine learning approach. *ICITEE 2020 - Proceedings of the 12th International Conference on Information Technology and Electrical Engineering*, 168–173. https://doi.org/10.1109/ICITEE49829.2020.9271683

World Bank. (2012). *Inclusive Green Growth*. https://doi.org/10.1596/978-0-8213-9551-6

Wulandari, S. A., & Wiranata, A. (2022). Kajian Kesejahteraan Petani kelapa Sawit Di Desa Talang Makmur Kecamatan Tebing Tinggi Kabupaten Tanjung Jabung Barat. *Jurnal MeA (Media Agribisnis)*, *7*(1), 18–28. https://doi.org/10.33087/MEA.V7I1.107

Xu, J., Gu, B., & Tian, G. (2022). Review of agricultural IoT technology. *Artificial Intelligence in Agriculture*, *6*, 10–22. https://doi.org/10.1016/J.AIIA.2022.01.001

Zhang, J., You, S., & Gruenwald, L. (2015). Efficient parallel zonal statistics on large-scale global biodiversity data on GPUs. *Proceedings of the 4th ACM SIGSPATIAL International Workshop on Analytics for Big Geospatial Data, BigSpatial 2015*, 35–44. https://doi.org/10.1145/2835185.2835187

Zongfan, B., Ling, H., Xuhai, J., Ming, L., Liangzhi, L., Huiqun, L., & Jiaxin, L. (2022). Spatiotemporal evolution of desertification based on integrated remote sensing indices in Duolun County, Inner Mongolia. *Ecological Informatics*, *70*, 101750. https://doi.org/10.1016/J.ECOINF.2022.101750