C-Band SAR-Based Backscatter Modeling for Monitoring Oil Palm Age

Hernawati, R.[1,2], Darmawan, S.[2], and Sumantyo, J.T.S[1,3]

[1]Department of Environmental Remote Sensing, Chiba University, Japan

[2]Department of Geodetic Engineering, Institut Teknologi Nasional Bandung, Indonesia

[3]Department of Electrical Engineering, Universitas Sebelas Maret, Indonesia

*rikah@itenas.ac.id)

Abstract: *Information regarding the age of oil palm trees serves as an essential metric for evaluating plantation productivity levels. Comprehensive method of age across entire plantations can enhanced management strategies, estimation of harvest projections, yield forecasting for fresh fruit bunches, tax assessment, replanting strategies, fertilizer application timing, and prompt identification of plant diseases. This research introduces remote sensing for modeling the age of oil palm trees using Synthetic Aperture Radar (SAR) technology, particularly utilizing C-band data with dual polarization capabilities. The study aims to investigate the correlation between SAR backscatter properties and the age of oil palm plantations. Sentinel-1A SAR images captured on November 14, 2022, were analyzed in conjunction with plantation block information indicating planting years spanning from 2000 to 2022. The analytical approach encompassed preprocessing procedures, radiometric calibration processes, speckle filtering techniques, terrain correction methods, scattering value extraction, and scattering model development. The results show moderate relationship between backscatter data and oil palm age, yielding classification accuracy rates of 78% for VV polarization and 71% for VH polarization. Subsequent studies may leverage SAR data to detect age-dependent structural modifications, while ground-based validation incorporating biophysical measurements and productivity data will enhance the credibility of remote sensing-derived age estimations.*

Keywords: *Oil Palm Age, SAR, C-band, Backscatter*

Introduction

Monitoring and evaluation of oil palm plantations play a vital role in advancing sustainable agricultural methods and effective ecosystem management (Shashikant et al., 2012). As a significant industry within tropical regions, oil palm cultivation has experienced rapid expansion, raising environmental concerns including forest degradation, biodiversity decline, and carbon emissions (Darmawan et al., 2021; Hernawati et al., 2022). Precise surveillance and assessment of oil palm estates are essential for formulating strategies to address environmental challenges while supporting sustainable production methodologies (Meijaard et al., 2018).

Synthetic Aperture Radar (SAR) technology, particularly employing C-band frequencies, has emerged as a powerful tool for this purpose due to its capability to penetrate cloud coverage and deliver high-resolution information independent of meteorological conditions

(Hernawati et al., 2024). SAR systems can capture backscatter information that exhibits substantial variation depending on surface properties (Nasirzadehdizaji et al., 2021). This capability presents an alternative approach for monitoring diverse crop parameters. However, the integration of phenological information in SAR research for oil palm cultivation remains inadequately explored (Darmawan et al., 2021). Previous studies has revealed the potential of satellite-based SAR technology for surveillance and assessment of oil palm estates (Darmawan et al., 2021); (Kee et al., 2018); (Trisasongko & Paull, 2020). Spaceborne SAR sensors functioning in the X-, C-, and L-bands have demonstrated capability in detecting and characterizing oil palm plantations through their distinctive scattering mechanisms and vegetation structure interactions (Darmawan et al., 2021). Furthermore, SAR data, including fully polarimetric datasets, has been effectively employed to map and monitor rubber plantations, which shows similarities to oil palm regarding vegetation structure and age-related transformations (Carolita et al., 2021; Trisasongko, 2017).

Accurate identification of oil palm tree age can be achieved by utilizing the significant relationship between canopy height, dimensions, and growth phase (Hernawati et al., 2024). Combining phenological information with SAR data can enhance crop monitoring precision and facilitate sustainable agricultural practice implementation (Pohl et al., 2016). Phenology, which examines growth stages and life cycle phases in plants, is fundamental for understanding plant development dynamics and environmental interactions (Darmawan et al., 2016). Exploring the connection between oil palm phenology and SAR backscatter data may substantially improve crop monitoring and management accuracy (Chong et al., 2017).

Therefore, this research seeks to create an adapted phenology-based backscatter model for oil palm utilizing C-band SAR, potentially contributing to sustainable agriculture development within the oil palm sector. We examine relevant research investigating remote sensing applications, especially SAR technology, for oil palm monitoring and the potential incorporation of phenological information to improve model accuracy, including studies by Carolita et al., 2019, 2021; Darmawan et al., 2021; Hernawati et al., 2024; Pohl et al., 2016; Trisasongko, 2017. We establish a framework for a phenology-based backscattering model for oil palm using C-band SAR, derived from our results and demonstrating the distinctive characteristics of oil palm plantations.

Methodology

The methodological approach encompasses several stages including data acquisition, preprocessing operations, radiometric calibration, speckle filtering, terrain correction, scattering value extraction, and scattering model devlopment (Figure 1).

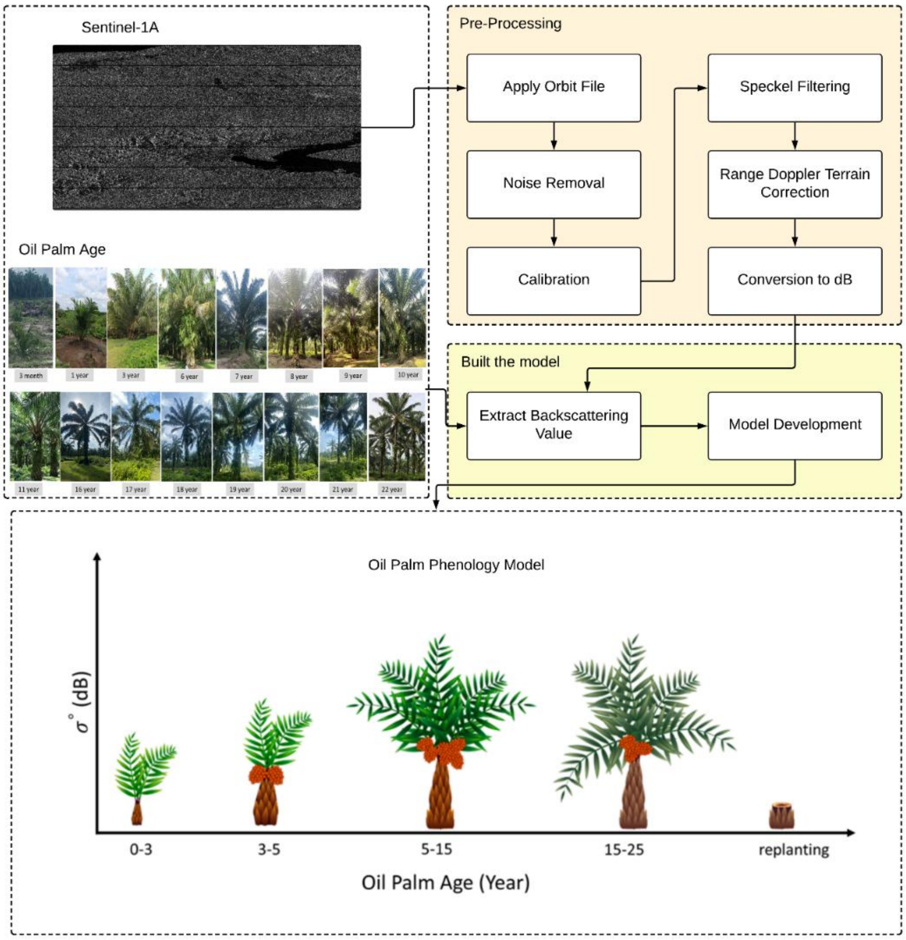


Figure 1. Methodology

SAR backscatter data underwent preprocessing, incorporating radiometric calibration, speckle filtering, and terrain correction procedures to acquire reliable backscatter coefficients. Field survey-collected phenological information was subsequently integrated with SAR backscatter data to determine correlations between backscatter signatures and various phenological stages of oil palm trees.

a. Study Area:

The research was performed at an oil palm plantation operated by PT. Perkebunan Nusantara III, situated in Sei Dadap, Asahan Regency, North Sumatra Province. The plantation encompasses approximately 6,075 hectares, as depicted in Figure 2. The study location is geographically positioned between 2°03' and 3°26' North Latitude, and 99°1' and 100°0' East Longitude. The study area's elevation varies from 0 to 1,000 meters above sea level. The plantation predominantly consists of oil palm trees across various age categories, from immature to mature stages, as illustrated in Figure 2.

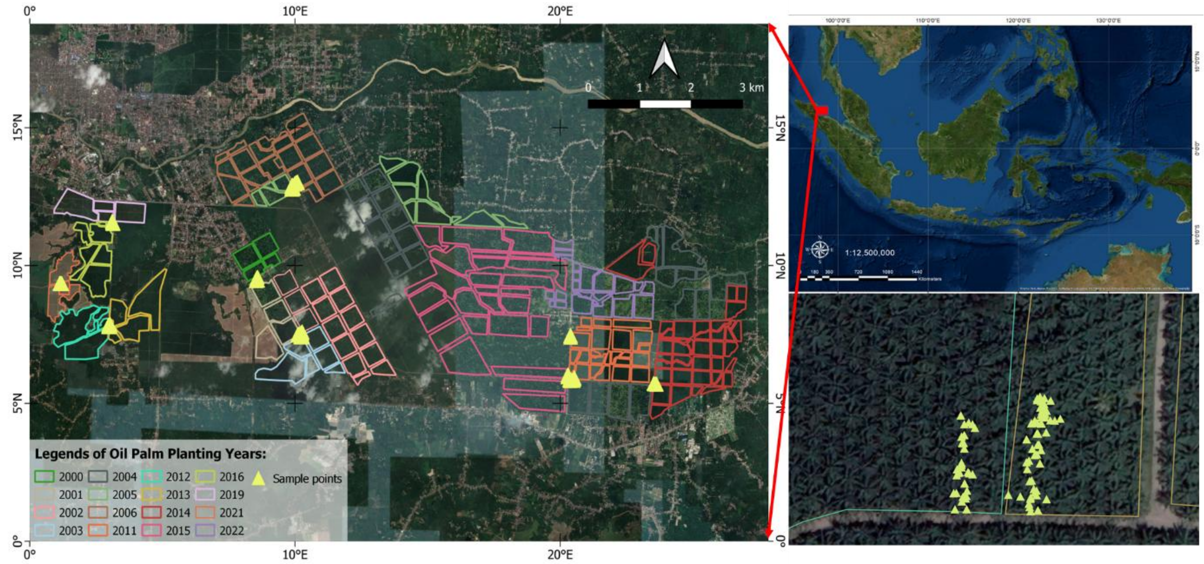


Figure 2. Study area

b. Data

Sentinel-1 synthetic aperture radar imagery was obtained on November 14, 2022, for the research locations. The dataset comprised Sentinel-1 Interferometric Wide swath Level 1 Ground Range Detected images, acquired in dual-polarization mode featuring vertical transmit and vertical receive, along with vertical transmit and horizontal receive polarizations. Additionally, oil palm planting year information was incorporated to determine phenology.

c. SAR Data Processing

Sentinel-1 Synthetic Aperture Radar (SAR) data processing incorporates orbit file application, thermal noise elimination, and radiometric calibration (Hernawati et al., 2023). The orbit file application function automatically retrieves and updates orbit state vectors, supplying precise satellite position and velocity information (Mandal et al., 2019). Thermal noise elimination normalizes the backscatter signal throughout the scene and reduces discontinuities between sub-swaths in multi-swath configurations (Mandal et al., 2019).

The Sentinel-1 GRD product contains calibration vectors and constant offset, which reverses the scaling factor from level 1 processing and implements the suitable rangedependent gain and absolute calibration constant. The conversion process from amplitude to Normalized Radar Cross Section (NRCS) in decibels using the calibrated gamma backscatter coefficient is examined (Darmawan et al., 2019), as described in Equation 1. The methodology involves automatic transformation of amplitude to Digital Numbers and from DN to normalized radar cross-section in decibels through SNAP software.

$$\sigma^{\circ}{}_{dB} = 10.\log_{10}[\gamma_i] \quad (33)$$

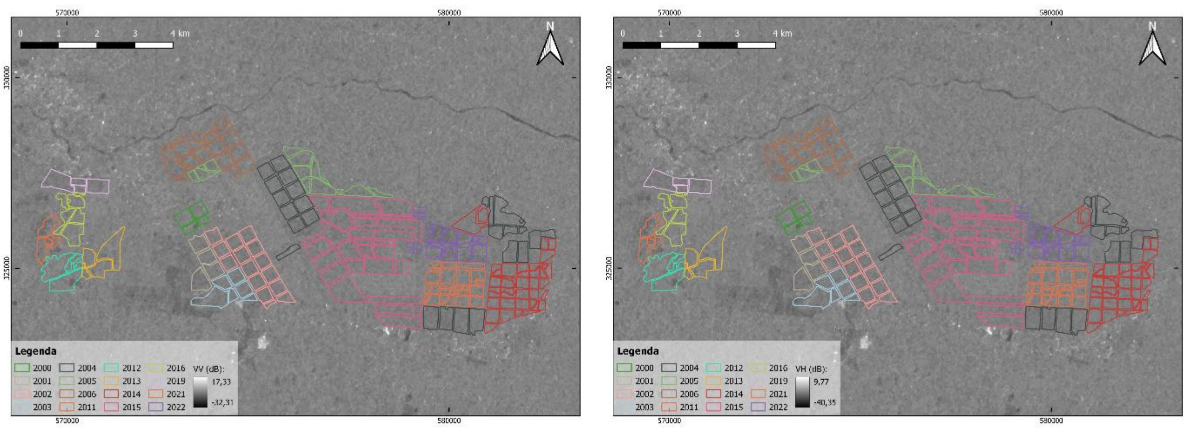
where γ_i is the calibrated gamma backscatter coefficient from the C-band sensor (Kee et al., 2018). The application of VV and VH polarizations in SAR imagery delivers valuable information for diverse applications by facilitating surface type and condition differentiation based on scattering characteristics (Braun & Offermann, 2022).

The research also addresses challenges in implementing optimal practices for SAR data calibration and processing, along with the necessity to evaluate SAR-specific imaging effects on final product quality. Subsequently, speckle filtering constitutes a crucial preprocessing stage that enhances image quality by reducing granular noise, while range Doppler terrain correction addresses geometric distortions inherent in SAR data acquisition.

Results and Discussion

a. VV and VH Polarization Oil Palm Plantation

The results indicate that VV and VH polarization measurements demonstrate high sensitivity to oil palm plantation characteristics, including tree age and growing phase.



(a) (b)

Figure 3. Visualization of (a) VV and (b) VH polarization data from Sentinel-1A

The visualization of VV (vertical-vertical) and VH (vertical-horizontal) polarization imagery from Sentinel-1A demonstrates distinct characteristics correlating with different stand ages of oil palm plantations (Figure 3). The findings indicate the sensitivity of C-band SAR data to phenological variations across the oil palm canopy. The distinctive backscatter patterns observed across different stand ages suggest that SAR data can effectively characterize the structural and dielectric properties of oil palm trees as they progress through growing phases.

Utilizing RGB composites of VV (vertical transmit, vertical receive) and VH (vertical transmit, horizontal receive) radar polarization data represents a valuable approach for distinguishing and characterizing diverse surface features according to their unique radar backscattering characteristics. This composite methodology exploits the sensitivity of these polarization modes to structural and dielectric properties of various land cover types, enabling improved land cover classification, environmental surveillance, and disaster management applications. By integrating these two polarization modes into composite imagery, researchers can effectively distinguish between healthy and diseased oil palm trees, and identify different developmental stages and management practices within plantations.

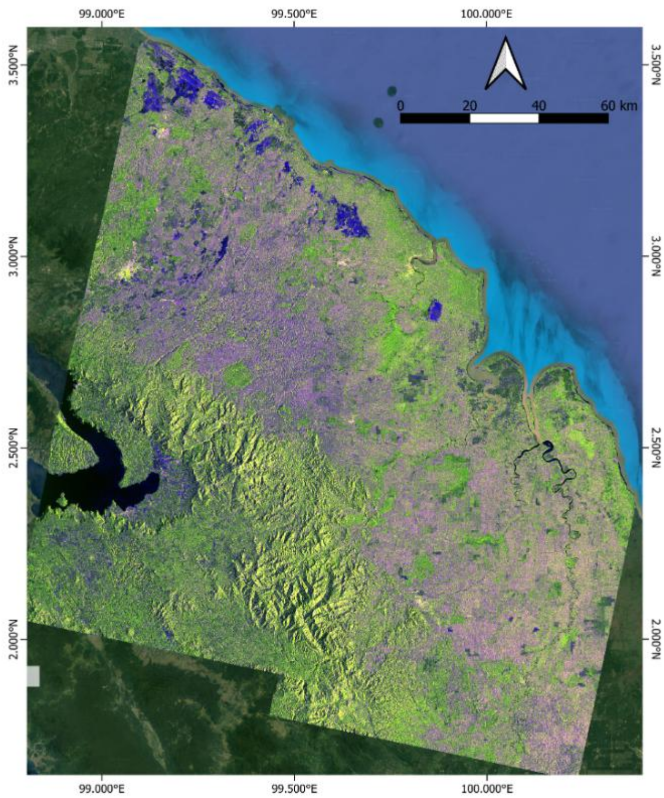
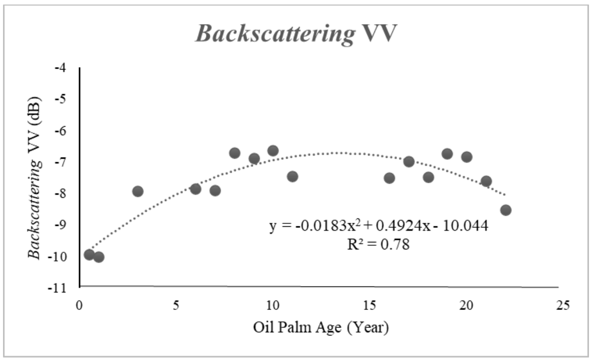


Figure 4. RGB composite of VV, VH, and VV+VH from Sentinel-1

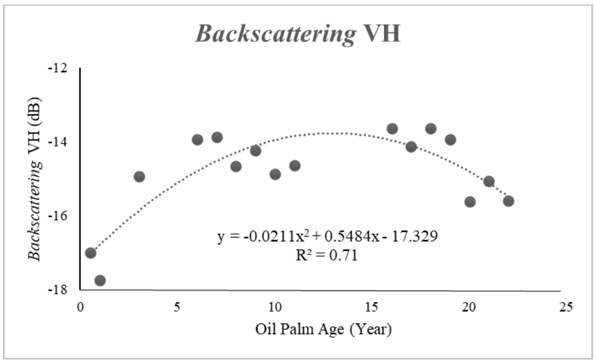
Figure 4, show dual-polarized Sentinel-1 data, specifically the VV and VH polarizations. Green and pink hues typically represent areas with elevated VH polarization, which generally indicates more random scattering likely produced by vegetation or anthropogenic structures. VH polarization is responsive to variations in orientation and geometric structure of objects, such as branches, foliage, and construction materials, which disrupt horizontal components of the radar signal. In contrast, purple and blue regions likely represent stronger responses in VV polarization, which is more sensitive to smoother surfaces and moisture levels. This polarization responds to surface roughness and water content, enabling clear detection of wet soils, flooded areas, or smooth surfaces including roads and well-irrigated fields.

b. Oil Palm Phenology Model Based on VV and VH Polarization

An oil palm phenology backscattering model for VV polarization was constructed based on collected field information and SAR measurements.



(a)



(b)

Figure 5. Model of oil palm phenology backscattering for (a) VV and (b) VH polarization

The scattering model for oil palm plantations in VV polarization (Figure 5a) begins at approximately -10 dB for ages 0-5 years, -7 dB for ages 5-10 years, -6.5 dB for ages 10-15 years, and -8 dB for ages 15-22 years. In VV polarization, the scattering model exhibits a nonlinear regression of $y = -0.0183x^2 + 0.4927x - 10.05$ with an R^2 value of 0.78 or 78%, where the first variable represents oil palm age, and the second variable represents the scattering polarization value, indicating that according to Hess (2017), the relationship between age and scattering value demonstrates a moderate correlation.

The scattering model for oil palm plantations in VH polarization (Figure 5b) initiates around -17 dB for ages 0-5 years, -15 dB for ages 5-10 years, -14 dB for ages 10-15 years, and -16 dB for ages 15-22 years. In VH polarization, the scattering model presents a nonlinear regression of $y = -0.0211x^2 + 0.5484x - 17.329$ with an R^2 value of 0.71 or 71%, where the first variable represents oil palm age, and the second variable represents the scattering polarization value, signifying that according to Hess (2017), the relationship between age and scattering value shows a moderate correlation.

Overall, the investigation determined that VV polarization displayed stronger correlation with oil palm phenology compared to VH polarization. This can be explained by the enhanced sensitivity of the co-polarized channel to the vertical structure of the oil palm canopy (Mandal et al., 2021). The backscattering properties of oil palm on VV and VH polarizations demonstrate that young oil palms exhibit the lowest backscattering values between 2 to 4 years old attributed to surface scattering. Mature oil palms display higher backscattering values between 7 to 14 years old resulting from double-bounce scattering. Older oil palms present lower backscattering values between 17 to 21 years old caused by volume scattering. This occurs because in newly planted areas, tree height is relatively limited and canopy size remains small, but when trees reach productive age, backscattering values increase due to differences in tree height and ground level (Darmawan et al., 2021; Hernawati et al., 2024).

Additionally, the shorter wavelength of Sentinel-1 or C-band results in smaller backscattering values for canopy density (Banqué et al., 2015). There is also considerable contribution from the trunk to the surface volume scattering component, although this is not the predominant component (Mandal et al., 2021). Volume scattering can also occur within the canopy of lower or sparser vegetation types at the shorter C-band wavelength (Darmawan et al., 2021). The radar signal is anticipated to be primarily scattered by foliage and upper branches and twigs of the canopy (Rignot et al., 1994). In Sentinel-1 dual-polarization data, the double-bounce component can affect VV polarization due to its sensitivity to vertical structure, particularly when aligned with the incoming radar wave (Nasirzadehdizaji et al., 2019).

Conclussion and Recomendation

The sensitivity of VV and VH polarizations to the structural and dielectric properties of oil palm enables fine-grained delineation of growth phases from young age to mature age. In this study, VV based classification achieved ~78% accuracy, while VH reached ~71%. Compared to VH, VV showed stronger relationship with oil palm phenology because the co-polarized channel is more sensitive to the canopy vertical structure.

Future research requires additional remote sensing data, including optical and thermal imagery, for further exploration of relationships between oil palm phenology, environmental parameters, and SAR backscatter data. Additionally, model verification across multiple oil palm plantation sites is necessary to ensure robustness and applicability for widespread monitoring and management.

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