# A phenology-based backscattering model for oil palm using C-band SAR

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**Abstract:** *Oil palm phenology data serves as a key indicator of production. Managing oil palm farms can greatly benefit from understanding phenological patterns, as this enables estimating harvest, fruit bunch yields, palm oil tax, replanting needs, fertilization requirements, and disease identification. This study aims to develop a technique that models oil palm phenology using remote sensing, particularly synthetic aperture radar techniques. The objective is to investigate an oil palm phenology model derived from C-band data using dual-polarization SAR scattering mechanism extraction. The radiometric data will be analyzed to establish the relationship between oil palm phenology. The study utilizes Sentinel-1A SAR imagery acquired on November 14, 2022, along with oil palm planting year block data to identify stand ages ranging from 2000 to 2022. The results demonstrate a strong relationship between oil palm phenology and the backscatter model, achieving an accuracy of 78% for VV polarization and 71% for VH polarization.*

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

## Introduction

Monitoring and assessing oil palm plantations is crucial for promoting sustainable agricultural practices and managing ecosystems effectively (Shashikant et al., 2012). Oil palm is an important industry in tropical areas; currently, its rapid expansion has caused concerns regarding environmental implications, such as deforestation, loss of biodiversity, and greenhouse gas emissions (Darmawan et al., 2021; Hernawati et al., 2022). Accurate monitoring and evaluation of oil palm farms are important for developing strategies for managing environmental issues and support sustainable production practices (Meijaard et al., 2018).

Synthetic Aperture Radar (SAR) technology, specifically using C-band frequencies, has become an effective instrument in this application since it can penetrate cloud cover and offer high-resolution data regardless of weather conditions (Hernawati et al., 2024). Synthetic Aperture Radar (SAR) can acquire backscatter information, which show significant variations based on surface characteristics (Nasirzadehdizaji et al., 2021). This provides an alternative method for monitoring various crops parameters. Nevertheless, the application of phenological data in synthetic aperture radar investigations within oil palm farming has not been thoroughly investigated (Darmawan et al., 2021). Previous studies have demonstrated the potential of satellite-based Synthetic Aperture Radar technology for monitoring and assessing oil palm plantations (Darmawan et al., 2021); (Kee et al., 2018); (Trisasongko & Paull, 2020). Spaceborne SAR sensors operating in the X-, C-, and L-bands have shown promise in detecting and characterizing oil palm plantations based on their unique scattering mechanisms and interactions with vegetation structure (Darmawan et al., 2021). Additionally, SAR data, including fully polarimetric data, has been successfully utilized to map and monitor rubber plantations, which share similarities with oil palm in terms of vegetation structure and age-related changes (Carolita et al., 2021; Trisasongko, 2017).

The age of oil palm trees can be accurately identified by applying the important correlation between the palms' canopy height, sizes, and growth phase (Hernawati et al., 2024). Integrating phenological data with SAR information can improve the accuracy of crop monitoring and support the implementation of sustainable agricultural practices (Pohl et al., 2016). Phenology, the investigation of phases of growth and life cycle phases in trees, is necessary for recognizing plant growth dynamics and their interaction with surrounding factors (Darmawan et al., 2016). Investigating the relationship between oil palm phenology and SAR backscatter information may significantly improve the precision of crop monitoring and management (Chong et al., 2017).

Therefore, this study aims to develop an adapted phenology-based backscatter model for oil palm using C-band SAR, which could contribute to the growth of sustainable agriculture practices in the oil palm industry. We investigate relevant studies that investigate the application of remote sensing, particularly SAR technology, for monitoring oil palms and the potential integration of phenological data to enhance the accuracy of these models such as (Carolita et al., 2019, 2021; Darmawan et al., 2021; Hernawati et al., 2024; Pohl et al., 2016; Trisasongko, 2017). We develop a framework for a phenology-based backscattering model for oil palm utilizing C-band SAR. This is derived from our findings and shows the unique characteristics of oil palm plantation.

## Methodology

The methodology includes the following steps including data collection, preprocessing, radiometric calibration, speckle filtering, terrain correction, extraction of scattering values, and building of a scattering model (Figure 1).

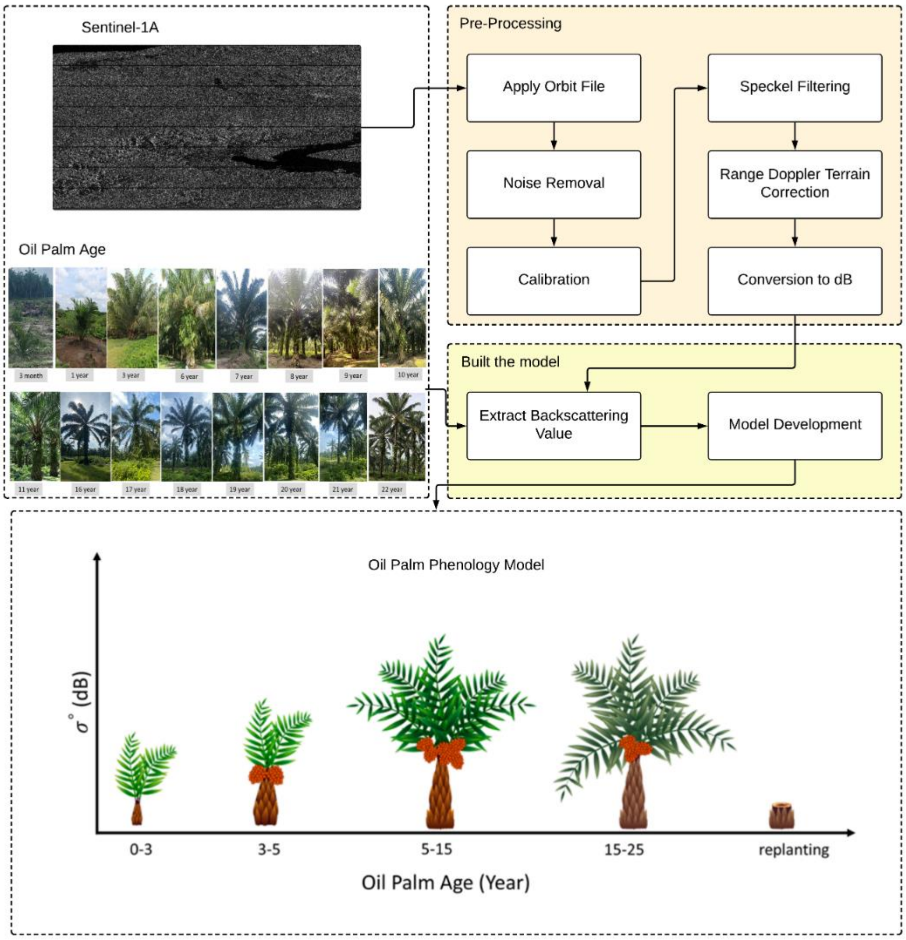



Figure 1. Methodology

The SAR backscatter data was preprocessed, including radiometric calibration, speckle filtering, and terrain correction, to obtain reliable backscatter coefficients. The phenological data collected from the field surveys was then integrated with the SAR backscatter information to establish correlations between the backscatter signatures and the various phenological phases of the oil palm trees.

### a. Study Area:

The study was conducted within the oil palm plantation owned by PT. Perkebunan Nusantara III, located in Sei Dadap, Asahan Regency, North Sumatra Province. The plantation spans approximately 6,075 hectares, as illustrated in Figure 2. Geographically, the study area is situated between 2°03' and 3°26' North Latitude, and 99°1' and 100°0' East Longitude. The elevation of the study area ranges from 0 to 1,000 meters above sea level. The plantation is dominated by oil palm trees of various ages, ranging from young to mature, as shown in Figure 2.

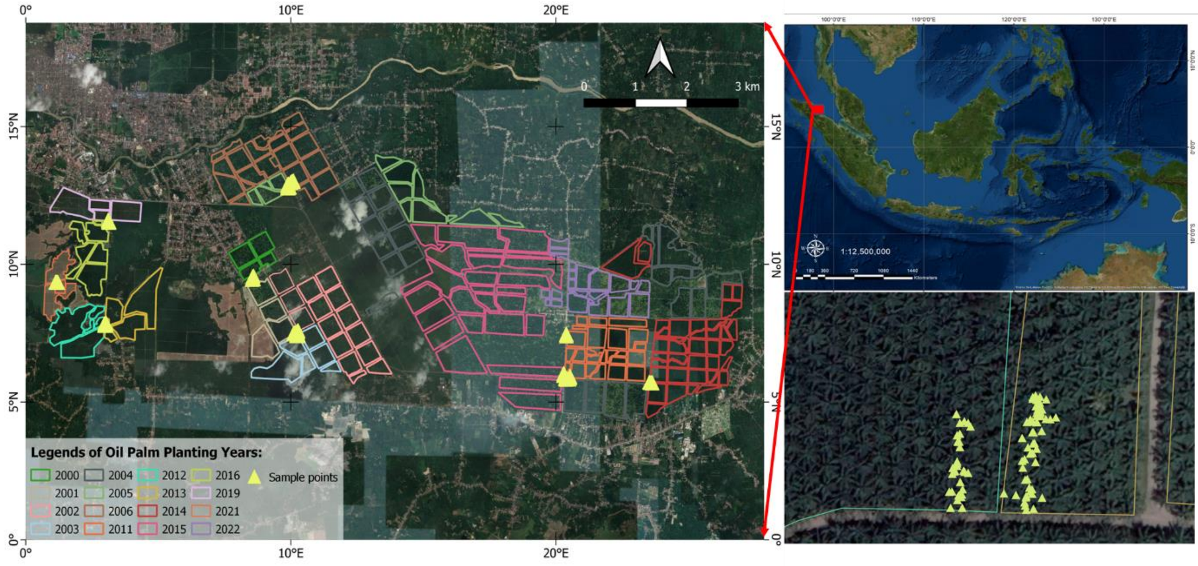



Figure 2. Study area

## b. Data

Sentinel-1 synthetic aperture radar data was acquired on November 14, 2022, for the study areas. The dataset included Sentinel-1 Interferometric Wide swath Level 1 Ground Range Detected images, captured in dual-polarization mode with vertical transmit and vertical receive, as well as vertical transmit and horizontal receive polarizations. Additionally, oil palm planting year data was utilized to estimate the phenology.

## c. SAR Data Processing

The Sentinel-1 Synthetic Aperture Radar (SAR) data processing involves apply orbit file, thermal noise removal, and radiometric calibration (Hernawati et al., 2023). The apply orbit file feature automatically downloads and updates the orbit state vectors, providing accurate satellite position and velocity data (Mandal et al., 2019). Thermal noise removal can normalize the backscatter signal within the scene and minimize discontinuities between sub-swaths in multi-swath modes (Mandal et al., 2019).

The Sentinel-1 GRD product includes calibration vector and constant offset, which reverses the scaling factor from level 1 processing and applies the appropriate range-dependent gain and absolute calibration constant. The process of converting amplitude to Normalized Radar Cross Section (NRCS) in decibels using the calibrated gamma backscatter coefficient is investigated (Darmawan et al., 2019), as described in Equation

1. The procedure involves automatic conversion of amplitude to Digital Numbers and from DN to normalized radar cross-section in decibels using the SNAP software.

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

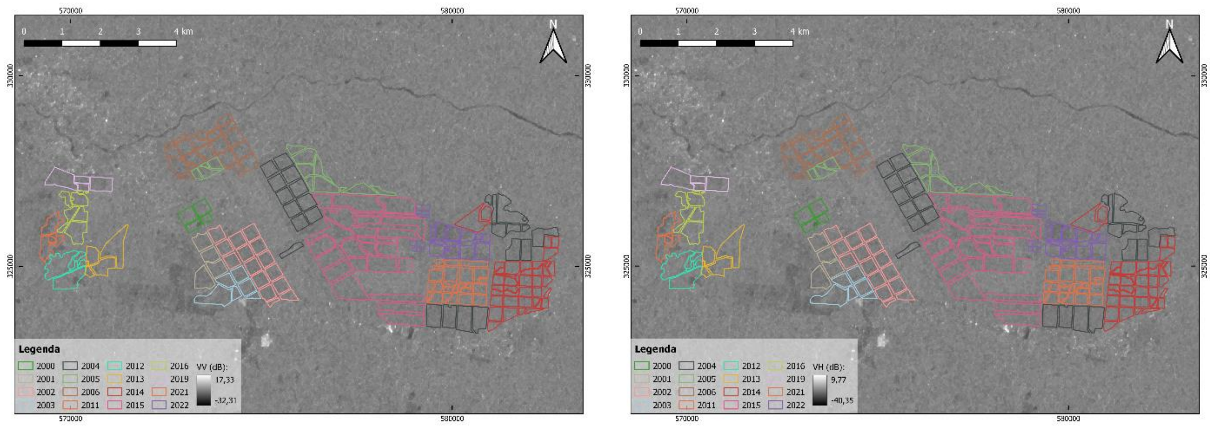
where $\gamma_i$ is the calibrated gamma backscatter coefficient from the C-band sensor (Kee et al., 2018). The use of VV and VH polarizations in SAR imagery provides valuable data for various applications by enabling the differentiation of surface types and conditions based on their scattering properties (Braun & Offermann, 2022).

The study also discusses the challenges in implementing best practices for SAR data calibration and processing, and the need to assess the influence of SAR-specific imaging effects on final product quality. Then, speckle filtering is a critical preprocessing step that can improve image quality by mitigating granular noise, while range Doppler terrain correction compensates for geometric distortions inherent in SAR data acquisition.

## Results and Discussion

### a. VV and VH Polarization Oil Palm Plantation

The results indicate that the VV and VH polarization values are highly sensitive to the characteristics of the oil palm plantation, such as the age and growth stage of the trees.




(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 data from Sentinel-1A imagery illustrates different characteristics that correlate with the various stand ages of oil palm plantation (Figure 3). The result shows the sensitivity of C-band SAR data to the phenological changes through the oil palm canopy. The unique backscatter indicates across various stand ages show that the SAR data might effectively indicate the structural and dielectric characteristics of oil palm trees, varying as the plants move forward through their growth phases.

The use of RGB composites of VV (vertical transmit, vertical receive) and VH (vertical transmit, horizontal receive) radar polarization data is valuable technique for differentiating and characterizing various surface features based on their unique radar backscattering properties. This composite approach leverages the sensitivity of these polarization modes to the structural and dielectric properties of different land cover types, allowing for enhanced land cover classification, environmental monitoring, and disaster management applications. By combining these two polarization modes into composite image, researchers can effectively differentiate between healthy and diseased oil palm trees, as well as identify different growth stages and management practices within the plantation.

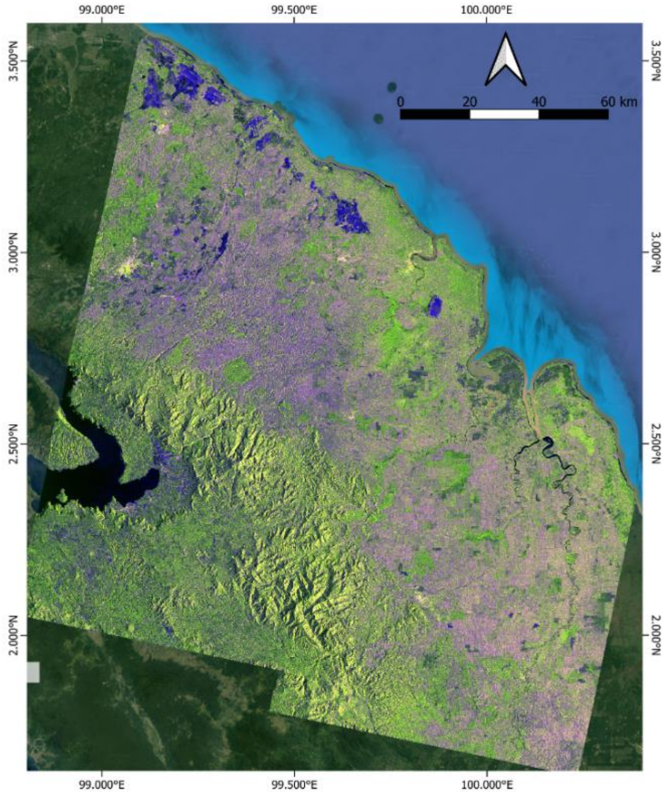
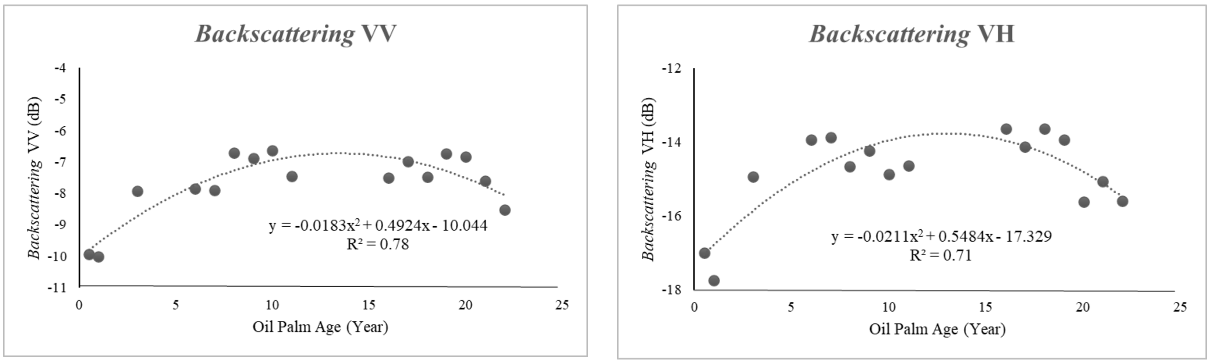



Figure 4. RGB composite of VV, VH, and VV+VH from Sentinel-1

Figure 4, show dual-polarized Sentinel-1 data, specifically the VV and VH polarizations. The green and pink colors often indicate areas with high VH polarization, which typically suggests more random scattering likely caused by vegetation or man-made structures. VH polarization is sensitive to changes in the orientation and geometric structure of objects, such as branches, leaves, and building materials, which disrupt the horizontal components of the radar signal. Conversely, the purple and blue areas likely represent stronger results in VV polarization, which is more responsive to smoother surfaces and moisture content. This polarization is sensitive to surface roughness and water content, allowing for clear identification of wet soils, inundated areas, or smooth surfaces such as roads and well-irrigated fields.

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

Model of oil palm phenology backscattering for VV polarization was developed based on the collected field data and SAR measurements.




(a) (b)

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

The scattering model of oil palm plantations in VV polarization (Figure 5a) starts at around -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 has a nonlinear regression of $y = -0{,}0183x^2 + 0{,}4927x - 10{,}05$ with an $R^2$ of 0.78 or 78%, where the first variable is the age of the oil palm, and the second variable is the scattering polarization value, which means that according to Hess (2017), the relationship between age and scattering value has a moderate correlation.

The scattering model of oil palm plantations in VH polarization (Figure 5b) starts 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 has a nonlinear regression of $y = -0.0211x^2 + 0.5484x - 17.329$ with an $R^2$ of 0.71 or 71%, where the first variable is the age of the oil palm, and the second variable is the scattering polarization value, which means that according to Hess (2017), the relationship between age and scattering value has a moderate correlation.

Overall, the study found that the VV polarization exhibited higher correlation with the oil palm phenology compared to the VH polarization. This can be attributed to the increased sensitivity of the co-polarized channel to the vertical structure of the oil palm canopy (Mandal et al., 2021). The backscattering characteristics of oil palm on VV and VH polarizations show that young oil palms have the lowest backscattering values between 2 to 4 years old due to surface scattering. Mature oil palms have higher backscattering values between 7 to 14 years old caused by double-bounce scattering. Older oil palms have lower backscattering values between 17 to 21 years old caused by volume scattering. This is because in new plantation ages, the tree height is relatively low and the canopy size is still small, but when the trees reach productive age, the backscattering values increase due to the difference in tree height and ground (Darmawan et al., 2021; Hernawati et al., 2024).

Additionally, the shorter wavelength of Sentinel-1 or C-band causes the backscattering values of canopy density to be smaller (Banqué et al., 2015). There is also a significant contribution from the trunk to the surface volume scattering component, although this is not the dominant 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 expected to be predominantly scattered by the leaves and upper branches and twigs of the canopy (Rignot et al., 1994). For Sentinel-1 dual-polarization data, the double-bounce component can influence the VV polarization due to its sensitivity to vertical structure, especially when aligned with the incoming radar wave (Nasirzadehdizaji et al., 2019).

**Conclussion and Recomendation**

The sensitivity of VV and VH polarization to the structural and dielectric properties of oil palm plants allows for detailed characterization of different growth phase. Effectively to monitor the evolution of the palm trees, from young to mature with the accuracy of 78% for VV polarization and 71% for VH polarization. The study found that the VV polarization shown had a higher correlation with oil palm phenology than the VH polarization. This is caused by the increased sensitivity of the co-polarized channel to the vertical structure of the oil palm canopy.

Future study requires additional remote sensing data, such as optical and thermal imagery, for further investigation of the relationships between oil palm phenology, environmental parameters, and SAR backscatter data. Additionally, we must verify the model across several oil palm plantation areas to ensure its robustness and suitability for wide-ranging monitoring and management.

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