CHAPTER 1
INTRODUCTION

1.1. Background

Tea is a plantation commodity in Indonesia. The management of the tea commodity involves three main players, namely State-Owned Plantations/PBN or PTPN, Private Plantations/PBS, and Smallholder Plantations (PR). Indonesia faces an imbalance between tea imports and exports due to high domestic demand that is not matched by low local production, forcing the country to import tea to meet domestic consumption needs [1]. However, over the past two decades, national tea production has shown a declining trend. According to the *Badan Pusat Statistik (BPS)*, production decreased from 165,194 tons in 2002 to 122,700 tons in 2023 despite relatively stable plantation areas in several provinces [2]. In 2023, the total plantation area reached 97,564 hectares with West Java contributing the largest share, namely 75,703 tons from 75,805 hectares, which is equivalent to 64.98% of national production [2]. Average national productivity is recorded at only 1.2 tons per hectare, lower than Kenya at around 2.5 t/ha and India at around 2.3 t/ha.

This decline in production is closely related to several underlying issues. The area of tea plantations has continued to shrink due to prolonged drought, pest infestations, and illegal encroachment [2]. Productivity has also experienced a slight but consistent decrease from 1.26 t/ha in 2017 to 1.25 t/ha in 2018 [3], which in turn affects the achievement of annual production targets. Furthermore, plant deaths caused by extreme weather events or disease are often not recorded promptly in the absence of updated population data, as noted by PPTK Gamboeng. This lack of accurate population information also affects resource management. Fertilizer application, for example, is typically based on land area rather than the actual number of plants, resulting in inefficient use of resources and increased production costs. Without precise plant population estimates, replanting needs are not well monitored, making it difficult to plan rejuvenation programs and to calculate the actual cost of production. Since plant population density directly influences yield per block, the inability to track population changes over time ultimately impacts total production output.

Current estimates of tea plant populations still rely heavily on manual surveys, which require significant manpower, are time-consuming, and prone to human error, particularly for large plantations with complex terrain [4]. Such methods also limit the scope and frequency of monitoring. In agricultural research, various alternative methods have been explored to address similar challenges in other crops. Satellite imagery combined with vegetation indices such as NDVI has been applied to crops like oil palm and corn [5], [6], but spatial resolution (0.3–10 m/pixel) is often insufficient to detect small structures like tea stalks. LiDAR technology can generate detailed canopy and plant height maps [5], but is expensive and sensitive to environmental conditions. Multispectral and hyperspectral imaging provides valuable insights into plant health and canopy characteristics [7], yet struggles to detect stalks hidden beneath dense foliage.

Unmanned Aerial Vehicles (UAVs) have emerged as a popular tool due to their high spatial resolution and operational flexibility [8], [9]. Multispectral UAVs have been successfully used to estimate tea yields [10] and monitor growth parameters such as Leaf Area Index (LAI) and Above Ground Biomass (AGB) [11]. However, in tea plantations, the dense canopy often obstructs the visual detection of stalk positions from above, reducing the accuracy of population estimates. Integrating UAV imaging with radar technology offers a promising solution. Radar, particularly FMCW radar, can penetrate dense foliage and is sensitive to variations in vegetation density [12], [13]. Studies have demonstrated its effectiveness in detecting biomass [14] and monitoring vegetation structures [15]. In parallel, Ground Penetrating Radar (GPR) has been used to estimate subsurface soil density with errors below 2.1% [16], and planetary radar sounding has measured electron density variations in the Martian ionosphere under different environmental conditions [17], showing radar's capability in detecting structural and density variations across diverse applications, making it a viable approach for accurate, efficient, and non-invasive estimation of tea plant populations.

1.2. Problem Statement

Tea commodities have different plant characteristics and planting patterns than other plantation commodities. These differences make it difficult to identify populations visually, so estimation methods using image processing alone will be less accurate. However, the dense surface characteristics of tea plant shoots and the high-density planting patterns result in variations in vegetation density. These variations in vegetation density make radar technology a potential tool for identifying density variations in tea plants. The reflection of electromagnetic waves in Radar technology can provide a wealth of information, such as density, distance, movement, and size. The electromagnetic waves reflected by Radar are influenced by the electrical characteristics of the medium or object, causing the reflection coefficient of the vegetation surface to vary according to the density of the medium or object. From the problems analyzed, an appropriate method is needed to estimate the population of tea plants by integrating the results of Radar signal processing and image processing. Therefore, the research questions in this study are as follows:

1. There is a need for a method to combine Radar signal data and image processing to detect the positions of tree trunks in tea plantations that are difficult to identify visually.
2. A deeper understanding is needed regarding the correlation between Radar signal parameters and conditions under the crop field that are influenced by tree stump positions.
3. Research is needed on the performance of density variation detection methods in vegetation media to estimate population density using Radar technology.

1.3. Research Objectives

The objective of this research is to investigate and develop a new approach to estimating tea plant populations by integrating cameras and radar on unmanned aerial vehicles (UAVs) or drones.

1. Designing methods or concepts for the elaboration of Radar technology in drone-based population estimation and image processing, with a focus on developing Radar technology that can be integrated with drone use and image processing to improve the accuracy of tea plant population estimation.
2. Designing methods for processing Radar signals to estimate the location of tea plant canes, with the aim of accurately identifying and determining the position of the main structure of tea plants, namely the canes.
3. Designing techniques to combine drone camera detection results with Radar signal results to estimate tea plant populations, with a focus on integrating data from various technologies to provide more comprehensive and accurate population estimates.

1.4. Hypothesis

In the context of estimating tea plant populations using radar and image processing, the concept of cross-medium propagation becomes important. Radar uses electromagnetic waves that can propagate through various media, including air and vegetation. When radar waves propagate through tea plants, they interact with the plants and are reflected back to the radar device. This cross-medium propagation affects how radar waves interact with tea plants. For example, the density and type of tea plant medium can affect how much radar waves are absorbed or reflected. Tea plants with high density tend to absorb more radar waves, while plants with low density tend to reflect more waves. Image processing is used to analyze the data obtained from the reflected radar waves. Using image processing techniques, we can identify and map areas in tea plantations with different plant densities. This allows us to estimate plant populations more accurately, as we can see where tea plants grow densely and where they grow more sparsely. The density on the surface of tea plants makes it difficult to identify tea plants visually and causes variations in the density of the vegetation medium. Radar reflectivity is influenced by the electrical characteristics of the medium or object, so the reflectivity coefficient obtained from the surface of tea plant vegetation varies according to the density of the vegetation medium. In this study, the electrical characteristics of the medium or object, such as tea plant stalks, can be explained using the basic equation of electromagnetic waves reflected by the surface of tea plants.

$$R = \frac{P_t G_t \lambda^2 \, \sigma A}{(4\pi)^3 R^4 L A_r} \tag{1}$$

Equation (1) describes the power reflected back to the radar (R) as a function of various parameters, including the power emitted by the radar (P_t), the radar antenna gain (G_t), the radar wavelength (λ), the reflectivity coefficient (σ), the target area (A), the distance between the radar and the target (R), the attenuation factor (L), and the effectiveness of the receiving antenna (A_r). When Radar waves are reflected by the surface of tea plants, changes in the density of the vegetation medium will cause variations in the reflectivity coefficient (σ). Using this equation, it can be more clearly explained that variations in the density of the vegetation medium in tea plants will result in changes in the reflectivity coefficient (σ), which will be reflected in the power reflected back to the Radar. Variations in vegetation density can be identified based on variations in the reflectance coefficient produced by the radar, enabling tea plants to be detected. Therefore, by understanding and analyzing these changes, radar technology has the potential to be used for more accurate detection and estimation of tea plant populations.

1.5. Methodology

This study will use an experimental research method with a multi-sensor drone approach, involving the integration of Radar technology and image processing on Unmanned Aerial Vehicles (UAVs) or drones. This approach will include several steps. The first stage of this study is to conduct a literature review on methods for detecting density variations using Radar and methods for estimating populations using image processing. This literature study will cover the basic concepts of Radar for estimating tea plant populations by detecting plant stalk and relevant methods, including image processing methods. Information from the literature study and preliminary research that has been conducted will be reviewed in the literature review section. The second stage is to identify the effect of density variation on the reflection coefficient. The third stage is to perform theoretical modeling and numerical simulation. The fourth stage is to design a method to combine Radar signal output with Camera output. This research combines radar as a plant stalk detection tool to calculate the population of tea plants, while the camera is used as a tool to detect the Region of Interest (ROI) of the tea plant field. The fifth stage is testing the theoretical and numerical simulations that have been modeled. The sixth stage of this research is laboratory/field experiments conducted to validate the proposed concept, followed by the development of an algorithm for data processing using the Radar-Camera technology integration method. Field testing was conducted at the Tea and Cinchona Research Center in Ciwidey. All research methods are detailed in Figure 1.5.1.

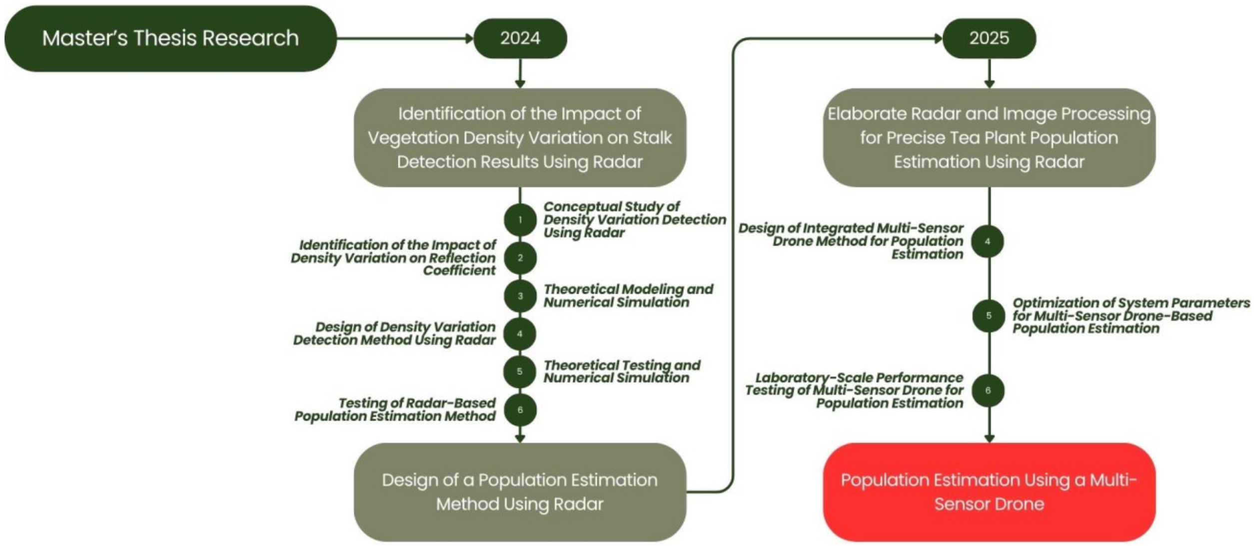

Figure 1.5.1 Research Method.

A more detailed explanation of the activities and milestones for each stage is provided in Table 1.5.1.

Table 1.5.1 Detailed Explanation of the Research Methodology

Num	Stages	Activities	Achievement Indicators
2024			
1.	Literature review in formulating basic concepts regarding density variation detection to determine plant location using radar.	Formulating research problems includes the principles of radar that will be used for target detection. Then, methodology and projection of needs.	The concept of density variation detection using a radar system and its extraction method.
2.	Identifying the influence of density variation on the reflection coefficient.	Identifying the influence of density variation when estimating population using Radar.	Understanding the influence of density variation on population estimation using Radar.
3.	Theoretical modeling and numerical simulation.	Conducting theoretical modeling and numerical analysis of the influence of density variation on detecting plant density.	Theoretical and numerical proof that density variation affects the reflection coefficient.
4.	Designing a method for detecting density variations using radar.	Designing a method for detecting density variations from the reflection coefficient.	Designing a method for detecting density variations using radar.

5.	Theoretical testing and numerical simulation.	Modeling objects with different density variations.	Radar can detect objects based on density variations.
6.	Testing the Radar population estimation method.	Collecting population data on tea plants.	Testing results document
2025			
7.	Design of Integrated Multi-Sensor Drone Method for Population Estimation	Designing the integration of radar and camera systems into a multi-sensor drone platform for tea plant population estimation, including the workflow and data fusion scheme.	A detailed multi-sensor system design and an integrated method for population estimation.
8.	Optimization of System Parameters for Multi-Sensor Drone-Based Population Estimation	Tuning and optimizing radar and camera parameters, including flight height, radar settings, image resolution, and synchronization between sensors to improve accuracy.	Optimized system parameters and improved accuracy in population estimation.
9.	Laboratory-Scale Performance Testing of Multi-Sensor Drone for Population Estimation	Conducting controlled experiments using a multi-sensor drone setup at laboratory scale or simulated field conditions to evaluate system performance.	Performance test report showing system reliability and population estimation capability at laboratory scale.

1.6. Implementation Schedule

The implementation of this research is scheduled in Table 1.6.1 below.

Table 1.6.1 Research Implementation Schedule

Num	**Activities**	**Month**																	
		2024												**2025**					
		1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6
1	Literature study in formulating basic concepts regarding density variation detection to determine the location of plant obstacles using Radar.																		
2	Identification of the influence of density variation on the reflection coefficient.																		
3	Theoretical modeling and numerical simulation.																		

4	Design of a method for detecting density variation using Radar.																		
5	Theoretical testing and numerical simulation.																		
6	Testing of the Radar population estimation method.																		
7	Analysis and refinement of the concept.																		
8	Publication and final report																		