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SUNYANI, GHANA

INFLUENCE OF SEASONAL CLIMATE VARIABILITIES AND PHENOLOGY OF MANGIFERA INDICA ON THE POPULATION DYNAMICS OF DIPTERA TEPHRITIDAE IN THE NADOWLI-KALEO DISTRICT, GHANA.

BY

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DEPARTMENT OF ATMOSPHERIC AND CLIMATE SCIENCE

SCHOOL OF GEOSCIENCES

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(MPhil. Development Studies, B.Ed. Agricultural Science)

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A THESIS SUBMITTED TO THE DEPARTMENT OF ATMOSPHERIC AND CLIMATE SCIENCE, SCHOOL OF GEOSCIENCES, IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN CLIMATE CHANGE

DECLARATION

I certify that this thesis is my original work based on research I conducted for the award of a Master of Philosophy degree in Climate Change and was directly supervised and presented under the rules and ethics guiding the supervision of thesis by the University of energy and Natural Resources. To the best of my knowledge, it does not contain any work published by another author or content accepted for a degree in the University or elsewhere without appropriate recognition and acknowledgement.

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ABSTRACT

Destruction of *Diptera tephritidae* has imposed quarantine restrictions and rapid economic losses in the horticulture industry. The nexus between agricultural productivity and climate change has garnered growing attention that requires scientific investigation. The study aims to examine the interactions between seasonal climate variability and the phenology of Mangifera indica on the population dynamics of *Diptera tephritidae,* anchored in climate ecology theory, phenological theory, population dynamics theory, and a systems ecological framework. Randomized Complete Block Design was adopted for the field layout, and Longitudinal studies were employed in gathering past and present data of fruit fly visitation and phenology of Mangifera indica, over a period of four production seasons. Climatic data were sourced from Ghana Meteorological Agency data base. Data analysis involved a generalized linear model and a Seasonal Harmonic Analysis. ANOVA test and multiple regression were performed, and a Random Forest regressor model was used for prediction. The model was trained on data from 2022 to 2024 and then tested to predict the fly count for the entire 2025. The study found a strong seasonal pattern in the fruit fly population. Total monthly rainfall and minimum temperature proved to be the most influential factors. In particular, rainfall showed a moderately positive correlation (r = 0.41) while minimum temperature showed a moderately negative correlation (r = -0.57). These results suggest that climatic conditions, especially during the rainy season and cooler months, play a crucial role in influencing the increase in fruit fly population. Phenology alone is insufficient as a predictor, but when considered in interaction with climatic variables especially temperature, it becomes a strong determinant. The study strongly recommends a longer-term data set and the inclusion of the fruit fly reproduction process and additional environmental variables to improve prediction accuracy.

DEDICATION

I dedicate this work entirely to my Boss and bosom friend Mr. Richard Ahiagbah and also in Memory of my late Auntie, Alima Bashiru Issahaque.

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LIST OF ACRONYMS

AMJ	April-May-June
ANOVA	Analysis of Variance
CET	Climate Ecological Theory
CUE	Cuelure
DDVP	Dichlorvos
GLM	Generalized Linear Models
GMET	Ghana Meteorological Services
IPC	Increased Production Cost
IPM	Integrated Pest Management
ITCZ	Inter-Tropical Convergence Zone
JAS	July-August-September
JFM	January-February-March
LCA	Linear Correlation Analysis
ME	Methyl Eugenol
MLR	Multiple Linear Regression
MLT	Machine Learning Techniques
MMT	Mean Maximum Temperature

MOFA	Ministry of Food and Agriculture
NOA	North Atlantic Oscillation
OND	October-November-December
PDT	Population Dynamics Theory
PHL	Post Harvest Loses
PPRSD	Plant Protection and Regulatory Service Directorate
PT	Phenological Theory
RFR	Random Forest Regressor
RTA	Regression Tree Analysis
SEF	System Ecology Framework
SHA	Seasonal Harmonic Analysis
TA	Terphenyl Acetate
TM	TriMed lure
TR	Trade Restriction

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Diptera tephritidae commonly known as fruit fly are globally recognized as one of the most destructive insect pests affecting fruits, particularly mango (Trombik et al., 2023). The female flies lay their eggs beneath the fruit's skin, and upon hatching, the larvae feed on the fruit's decaying flesh (Manrakhan, 2024). This infestation leads to rapid fruit decay, rendering the produce inedible or causing it to fall prematurely, thus resulting in direct economic losses for farmers. In addition to the physical damage caused by fruit fly, a series of quarantine restrictions is imposed by importing countries, further exacerbating indirect losses, limiting the trade of horticultural products especially between Africa and developed nations where the presence of fruit fly species has been confirmed (Jabik & Bawakyillenuo, 2022; Opoku et al., 2025). Since the introduction of *Bactrocera invadens to* Africa in 2003, the specie *Bactrocera invadens* has caused significant economic damage across the continent, with infestation levels ranging from 30 to 100% depending on the fruit's maturity, variety, location, and season (Grechi et al., 2021).

Mangifera indica, commonly known as mango is an important fruit crop, both globally and within the African sub-region, providing substantial benefits such as nutrition, employment, and export value (Arinloye et al., 2017; Jabik & Bawakyillenuo, 2022; Yiran et al., 2023; Dos Santos Moreira et al., 2024). However, mango production is frequently threatened by pests, and the fruit fly remains one of the most damaging pests.

The fly infestation and its effects extend beyond lower yields to post-harvest losses, reduced produce quality, and decreased market value of mango products. These issues lead to farmers' poverty and impact the local economy (Mulungu et al., 2023; Opoku et al., 2025).

Recently, climate change impacts on agriculture have gained significant attention and establishing the nexus between these critical areas is a major concern. Fluctuations in temperature, rainfall, and humidity are among the variables shown to affect the biological processes of most living organisms, including the fruit fly pest (Sthapit et al., 2012; Lee et al., 2020). That notwithstanding, the phenology of the mango tree, such as flowering, fruit development, and maturation, equally influences the population and distribution of the fly. Choudhary et al. (2021) postulated that key phenological stages such as fruiting and ripening create an enabling condition for the reproduction and infestation of the mango fruit fly. It is therefore imperative to investigate how the combined effects of climate variables and mango phenology influence fruit fly population dynamics and to devise appropriate control and management strategies against the invasive pest.

Mango production plays a vital role in the local economy, and the livelihoods of smallholder farmers in Ghana and the Nadowli-Kaleo District are no exception, since a tree crop has immense value in areas such as nutrition, herbal medicine, income sources, and more, with many rural farmers growing this economic tree in their backyards.

Nonetheless, the increasing effects of climate change may exacerbate fruit fly infestation rates, which have dire consequences for the mango industry (Sthapit et al., 2012; Lee et al., 2020) Considering the significance of this issue, there has been limited literature pointing to the combined effect, seasonal climate variability and the phenology of mango in determining and predicting the population dynamics of fruit flies, especially the Upper West Region of Ghana and the Nadowli-Kaleo district precisely. This study therefore aims at bridging the knowledge gap by examining how climate variables and the various phenological stages of the mango tree influences the population of the fruit fly.

The findings of this study will contribute to the development of sustainable pest management strategies, improving mango yields and bolstering the resilience of local farming communities to realize the full potential of mango production and to further enhance the suitability of the mango production and the horticulture industry at large.

1.2 Problem Statement

Notably, *Mangifera indica* is an important fruit crop in Ghana, contributing significantly to local livelihoods and the national economy through both domestic sales and export earnings as well as providing affordable nutrition to citizens. However, mango production is under persistent threat from the mango fruit fly especially *Bactrocera invadens* a major pest that causes considerable losses by damaging fruits, reducing yields, and diminishing market value (Zhao et al., 2024). The profound infestations lead to lower yields and this is directly linked to decreased income generation on the part of the farmers thus stretching to restricted access to lucrative exports markets (Kruger, 2016). Despite the widespread acknowledgment of the pest's effects (Zhao et al., 2024), efforts to manage it remain inadequate, largely due to gaps in understanding its population dynamics.

One of the critical knowledge gaps lies in the limited understanding of how climatic variables such as temperature, rainfall, and humidity affect the seasonal fluctuations of mango fruit fly populations abundance and range especially in developing predictive models on a scientific basis to combat the pest menace (Gutierrez et al., 2021). Furthermore, the role of mango phenology, specifically the flowering, fruiting, and ripening, and how the various growth stages influence fruit fly infestations is equally understudied in the Guinea savannah enclaves of the country. Narveh Awarikabey et al. (2023) conducted a study on mango phenology and fruit fly population dynamics in Ghana with a focus on the study to the transition zone. Also, the interaction between these phenological stages and climatic conditions, and how they jointly contribute to the population dynamics of the fruit fly, has not been extensively studied. Moreover, studies that have also examined climate influence on mango phenology and fruit fly infestation are geographically limited and the Nadowli-Kaleo district has received little documentation. This lack of knowledge limits the ability of farmers, agriculture extension officers, and pest management programs to anticipate and mitigate fruit fly infestation effectively.

Without a comprehensive understanding of how climate variability interacts with mango growth stages to influence fruit fly population dynamics, pest control strategies remain reactive and less effective (Ahmad et al., 2025). As climate change introduces more unpredictable weather patterns, this challenge becomes even more critical (Hulme, 2003). The inability to predict fruit fly outbreaks, particularly during sensitive mango growth stages, leads to suboptimal pest control measures and continued economic losses for farmers (Hoskins et al., 2023).

Therefore, this study seeks to bridge the knowledge gap by exploring how climate variabilities and mango phenology influence the population dynamics of the mango fruit fly in the NadowliKaleo District. Understanding these dynamics is essential for developing targeted, sustainable pest management strategies to mitigate the economic impacts of the fruit fly and enhance the productivity and profitability of mango farming in the region.

1.3 Aim and Objectives of the Research

1.3.1 Aim of the study

The main aim of the study is to examine the interactions of seasonal climate variabilities and the phenology of *Mangifera indica* on the population dynamics of *Diptera tephritidae*. With a thematic theme analysis of the multidimensional environmental and biological interactions within the ecosystem.

1.3.2 Specific Research Objectives

1. To assess the influence of climate variabilities on the seasonal population trends of mango fruit fly as an economic pest

2. To analyze the relationship between mango phenology and the population dynamics of the mango fruit fly.

3. To determine the interaction between mango phenology and climatic conditions in predicting future mango fruit fly infestations.

1.4 Research Questions

1.4.1 Main research question

How do seasonal climate variabilities and mango phenology influence the population dynamics of fruit fly as an economic pest in the Nadowli-Kaleo District**.**

1.4.2 Specific research questions

1. What is the relationship between climatic variables (temperature, rainfall, humidity) and the seasonal population trends of the mango fruit fly in the Nadowli-Kaleo District?

2. How do different phenological stages of mango trees (flowering, fruiting, ripening) affect the population dynamics of the mango fruit fly in the Nadowli-Kaleo District?

3. How do the interactions between mango phenological stages and climatic conditions influence the likelihood and severity of mango fruit fly infestations in the Nadowli-Kaleo District?

1.5 **Significance of the Study**

Mango production in Ghana is widely regarded as a vital agricultural activity, making significant contributions to the national economy and rural livelihoods (Arinloye et al., 2017). Despite this, the fruit is highly susceptible to the fruit fly, a pest of quarantine concern that causes loss and damage along the mango value chain, thereby affecting market value and leading to export restrictions due to stringent measures imposed by regulatory bodies and quality standards agencies (Kruger, 2016; Megha et al., 2023). The findings of the study will substantially contribute to the existing literature on the interaction between climate variables and mango phenology and their effects on the fruit fly population dynamics. A critical insight into the effects of these variables will offer an informed decision on the control and management strategies of the mango fruit fly pest.

Additionally, another significant contribution of the study focuses on the role of seasonal climate in predicting fruit fly population trends.

As a result of climate change, weather patterns have experienced a significant shift and variations, understanding these shifts in climatic factors such as temperature, rainfall and humidity along with the respective phenological stages of the mango tree has courted some prominence for scientific investigation (Dore, 2005; Yadav et al., 2023).

Understanding the seasonal climatic variation and the general concepts that influence fruit fly population on mango, will provide robust data in predicting the potential seasonal outbreaks of the fruit fly thus enhancing control measures and adaptive strategies in safeguarding the yields and estimated value of the orchard since it is an economic pest in the horticulture industry (Khan et al., 2021). Moreover, the study will provide in-depth knowledge on the phenological stages such as flowering, fruiting and ripening and how the interaction with various climatic variables influences the population distribution and abundance of the fruit fly (Michel et al., 2021a). Understanding the specific time periods and peak seasons of the fly will inform farmers of the appropriate pest control strategy to optimize production and safeguard the environment for sustainable production. In terms of policy, the study outcome will provide critical data for the government and key stakeholders such as the Plant Protection and Regulatory Services Directorate (PPRSD) at the Ministry of Food and Agriculture (MoFA), as well as the private sector, to guide in national policy formulation. A well-informed policy will guide effective pest management particularly in addressing the menace of mango fruit fly pest situation in Ghana and the sub region. Additionally, regulatory frameworks will be strengthened to safeguard the quality of mango exports and ensuring compliance with both local and international standards thereby enhancing the competitiveness of Ghanaian mango products at the global market for economic development (Ekesi et al., 2016).

Furthermore, key recommendations from the study outcome, when adopted by farmers will be practically useful, informing farmers to implement effectively fruit fly management techniques, hence optimizing production and increasing profitability (Muriithi et al., 2021). Mitigation of fruit fly infestation will position farmers well in quality production, higher yields and attract export demands of Ghanaian mango products at the global market.

The study will also serve as a blue print for cooperate entities and individuals exploring investment avenues in the mango industry. With an appreciable knowledge of how climatic variables, mango phenology and the fruit fly infestation intersect, investors are well equipped to allocate resources for sustainable production whiles minimizing risk and maximizing profits.

Holistically, the study aimed at promoting sustainable mango production, safeguarding farmers' economic livelihoods, ensuring environmental sustainability and to provide critical data for policy formulation, whiles positioning Ghana in the global mango industry for economic growth.

1.6 **Limitations and delimitations of the Study**

Delimitation of the study with regards to climatic data creates an impression of data accuracy, which may be affected by inconsistencies in local weather station measurements. The study was limited to four production seasons and four phenological stages ie vegetative, flowering, small fruits stage and large fruits stage (refer to appendix I for phenology interpretation), which may not fully capture long-term data and production cycles such as post-harvest stages. Moreover, the study was geographically limited to the Nadowli-Kaleo district at Matco Mango Plantation in the Guinea savannah zone of the country.

1.7 **Organization of the study**

The study is structured into five chapters. The first chapter deals with the background of the study, the significance, objectives, rational and limitations. Chapter two encompasses the literature review; which contains the theoretical and empirical underpinnings of the study, the conceptual and analytical themes. The third chapter delve into the research methodology and materials used in the research process. Chapter four presented the results and discussions, while chapter five summarizes the findings, draw conclusions and offered recommendations from the study outcome.

CHAPTER TWO

LITERATURE REVIEW

2.1 **Theoretical and Conceptual Underpinnings**

The study of the influence of seasonal climatic factors and phenology of mango tree on the population of mango fruit fly is multidimensional; hence the study is anchored on the climate ecology theory (CET), phenological theory (PT), population dynamics theory (PDT) and the systems ecology framework (SEF). These theories in line with the empirical basis of the study provides a clear appreciation of the study(Wacker 1998). Hence, how environmental and biological factors interact to influence the fruit fly population especially under a changing climatic condition.

2.1.1 Climate ecology theory

The climate ecology theory as articulated by Hunter (2011) suggest that the distribution, abundance and behavior of living organisms such as the fruit flies are influenced by climatic factors such as temperature, rainfall and humidity, and this is most common to ectothermic species such as insects. The evolution of this theory as dated back in the 18th – 19th centuary by Carl Linnnaeus and Alexander Von Humboldt, postulated that climate has a direct influence on on plants distribution and that vegetation zones have a correspondence to the respective climatic zones Hunter (2011). According to Huang et al. (2020a) the pest *Diptera tephritidae* experience fluctuations in these prevailing climatic conditions which affects the reproduction, survival and distribution patterns.

Contextually, the Climate Ecological Theory however sets the tone for analyzing and understanding how seasonal weather parameters and interannual climate influence the occurrence of the *Diptera tephritidea*. A growing body of literature, including Aplet & Mckinley (2017); Deutsch et al. (2008); Parmesan (2003), have shown that climate change can increase pest pressure by altering life cycles and expanding geographical ranges. This theory provides a solid background of the objectives especially in assessing the effects of climate variability on the seasonal fruit fly population trends.

2.1.2 Phenological theory

The phenology theory is concerned with the recuring biological activities of living organism with respect to time and season under prevailing environmental conditions which idea began with primitive farmers (Park & Post, 2022). According to Park & Post (2022) the growth stages of a plant including; flowering, fruiting and senescence plays a vital role on the influence of plant pest behavior such as the fruit fly. As the various growth stages of the mango provides ideal conditions for the biological success of the pest. The mango phenology therefore remains crucial factor as the theory assumes in the early 20th century and becomes an important discipline (Narveh Awarikabey et al., 2023). This theoretical underpinning allows space to analyze how the availability of flowers and fruits at various stages of growth influence the population abundance of the fruit flies within a particular seasonal climate pattern with the introduction of modern technologies in forecasting (Ibrahim et al., 2022). Some other studies including Yonow et al. (2004), establishes a synchronization effect between the insect behavior and the phenology of host plant. This theory supports the research objective in analyzing the relationship between mango phenology and the fruit fly population dynamics.

2.1.3 Population dynamics theory

There has always existed a rise or fall in Population as a result of several factors (Ashraf &

Galor, 2008). The population dynamics theory as posited by Thomas Malthus in 1798, articulated in Peter Kareiva (1990) analyses how population of organisms change over time. The Population Dynamics Theory (PDT) suggests that predatory activities within the insect's ecology, climatic factors and food availability such as fruits influences the population with regards to reproduction cycle and distribution of the insect (Kindlmann et al., 2007).This theory therefore assumes that due to interactions between birth and death rates, environmental conditions, competition for survival and resource availability are the decisive factors for the change in population of organisms such as the fruit fly. The modelling was based on these assumptions to determine pest outbreaks, whiles conscious of both biotic and abiotic factors which helps in predicting specific seasons and conditions under which the fruit fly thrives as posited by (Michel et al., 2021a). The PDT approach lays a foundation for the third objective which aims at determining the interactions between mango phenology and climatic conditions in predicting future occurrences and infestation rates of the mango fruit fly.

2.1.4 The system ecology framework

The integration of the various theoretical underpinnings offers a framework that guides the study and data analysis. This framework takes into consideration the inter-dependencies and relationships between environmental factors in the ecosystem network as the theories cannot standalone (Creamer et al., 2016). The system ecology framework combines the role of climate, plant phenology, pest ecology and human agricultural practices.

This approach views the mango cultivation system as a dynamic entity in which changes in one component (e.g. precipitation patterns) can have cascading effects on other components e.g. the behavior of fruit fly or the phenological timing (Yadav et al., 2024)

The framework is critical for the development of IPM strategies which allows the study to analyze interactive responses from the ecosystem perspective that are conscious of environmental and climate factors as well as human agricultural practices.

2.2 **Analytical themes of the study**

The theoretical underpinning of the study is functional through four central themes, each of the themes aligns and corresponds with identified specific objectives of the study.

2.2.1 Seasonal climate variability and the population dynamics of fruit flies

The unpredictability of seasonal climate patterns poses severe challenges for the control and management of pest and diseases which affects crops yield (Srinivasa et al., 2022). *Diptera tephritidae* are among the dangerous economic pest in the horticulture industry, and Michel et al. (2021b) opined that their population dynamics are highly sensitive to environmental factors. The research analysis the complexities existing between the fluctuating seasonal climate variabilities and the population dynamics of the fruit fly in the mango production.

According to (Follett et al., 2019) *Bactrocera and Ceratitis* are some common species of the fruit fly that are known for rapid reproduction capacity with a greater potential of fruit damage especially mango fruits. Just like many other species of the genera, their life cycle begins from the egg to larva, pupa and to adult. These life cycle stages are greatly influenced by micro climatic conditions. Higher temperatures are noted to accelerate the development and frequency of the population abundance of the fruit flies, whiles heavy rainfall and prolong droughts can suppress the growth and development of certain life stages of the insect pest (Anjum et al., 2017)

Considering the rapid changes of climate variables and seasonal variations, it is essential to underscore the ecological effects and response of the mango fruit fly amidst the changing climate variabilities. The phenomenon is investigated through a Seasonal harmonic Analysis to decompose how past and present climate information correspond with fruit fly population dynamics.

2.2.2 Interaction between Mango plant phenology and fruit fly population

Establishing the relationship between the mango fruit fly and the plant phenology as the host is critical for advancing effective pest control and management strategies. In mango production systems, phenological stages such as flowering, fruit set and fruit ripening create different time windows for the establishment and infestation of pests, especially *D. tephritidae.* These phenological changes influence the availability and quality of resources, which in turn affects the abundance, reproductive success and spatial distribution of fruit fly populations (Narveh Awarikabey et al., 2023)

This study investigates the relationship between mango development stages and fruit fly population fluctuations, with a focus on identifying critical phenological phases associated with increased infestation risk. The study is based on the hypothesis that certain phases of mango phenology, such as early fruit development and ripening, provide optimal conditions for oviposition and larval development, thereby influencing the timing and extent of population peaks(Yadav et al., 2024; Ahmad et al., 2025).

Phenological observations in the field were conducted simultaneously with systematic fruit fly trapping and sampling to determine the relationships between fruit availability and fruit fly abundance. The combined study of phenological stages of the plant and the fruit fly mentoring at a particular season is targeted at identifying seasonal trends of fruit fly infestation and the best distribution rate at every growth stage of the mango plant. This helps to determine the periods at which the mango tree is susceptible to the fly's infestation, develop models to predict the pest outbreaks based on observable phenological signals (Michel et al., 2021b).

Additionally, the temporal- ecological framework adopted for the study aims at assessing the delay effects, whereby the mango fruit fly may respond to the late development of certain phenological stage of the tree crop under prevailing environmental conditions such as temperature, rainfall and humidity. Understanding these patterns enables the communication of early warning systems and targeted pest control mechanisms (Reichstein et al., 2025).

The study largely focused on contributing a deeper scientific comprehension of the ecological synchrony between the mango tree as a host and the fruit fly as a pest of the orchard, whiles providing evidence-based solutions for IPM strategies. This is particularly of immense value in understanding the interplay between fruit fly ecological behavior and the appropriate management techniques (Sarker et al., 2009).

2.2.3 Interaction between the tree phenology and climate variables

According to Rodovitis et al. (2024), several factors including both biotic and abiotic independently influence the abundance and development of fruit flies. The impact of climate extremes and the interaction with growth stages of the mango plant is crucial in the population density of the fruit fly pest (Sthapit et al., 2012). Extant literature however emphasized the increasing impacts of these variables and how they jointly influence each other. However, their interactions are often determined by the time of the season, the extent and the spatial distribution of the fruit fly pest (Khan et al., 2021).

The phenology of the mango therefore refers to the respective growth stages of the mango tree as a driver of the fruit fly's ecological behavior that influence the population and availability. The phenology therefore encompasses the occasion of recurring biological events of the plants; such as flowering, fruit development and maturation etc. Narveh Awarikabey et al. (2023) opined that these phenological phases in mango forms different ecological windows that influence the general behavior and reproductive cycle of the insect pest. In a similar study, Grechi et al. (2021) alluded that the fruit fly infestation is higher during the ripening stages which creates an optimal and conducive space for egg laying and larval development. It is therefore important to connect the nexus of this temporal overlap of phenological susceptibility and fruit fly infestation.

Abiotic factors such as climate conditions; especially temperature and rainfall have a great influence on the physiological development, reproductive cycle, survival rate and spatial distribution of the fruit fly (Lakhnarayan et al., 2023). Higher temperatures are associated with the population abundance by accelerating the life cycle of the insect. Whiles rainfall influences the availability of alternative host and larva protection. These key variables are integrated into ecological niche and other models for the prediction of future occurrences of the fruit fly.

Nonetheless, there have existed limited literature on the combined effects of the interaction between phenological attributes, climate extremes and the fruit fly population dynamics (Choudhary et al., 2021a). Recent studies in ecological modelling however suggested that climate effects is a key determinant of the surge in fruit fly population during the phenological stages. This therefore implies that, the variables under study cannot function in isolation in determining the availability of the fruit fly (Yonow et al., 2004). As observed by Ponti &

Sannolo (2023), increased temperature can only have an effect on the fly’s abundance during the fruiting stage.

To effectively understand the interaction of these variables, researchers employed several models and regression analysis to quantify the effects. Coll et al., (2011) suggested that generalized linear models (GLM) are adopted to test the interaction between phenology and climatic variables while Regression Tree Analysis (RTA) is helpful to uncover the non-linear relationships and thresholds. These models have proven to be effective in modelling the fruit fly outbreaks during optimal climatic conditions which might coincide with certain phenological phases such as ripening of fruits.

Given the implications for pest control and forecasting, the literature concludes that pest control strategies focusing solely on climatic conditions or calendar schedules may be insufficient. Instead, integrating monitoring systems with real-time climate data could improve the accuracy of early warning systems and the timing of interventions especially in agriculture. (Yu et al., 2025). For example, the use of traps or biological control agents during fruit ripening under humid and warm conditions can significantly reduce infestation (Ippolito & Nigro, 2000). Although the interactions between climate and mango phenology are well known, there are few empirical studies that quantitatively model these interactions in the West African context (Choudhary et al., 2021b) . Ghana in particular, there are hardly any systematic studies on how seasonal climate fluctuations interact with mango phenology and influence *Diptera tephritidae* populations. The present study attempts to fill this gap by investigating these interactions using phenological observations in the field and climate data analyzed with robust statistical models. The results will serve as a basis for region-specific pest control strategies and improve our understanding of the ecology of fruit flies under changing climatic conditions.

2.2.4 Predictive modelling and fruit fly forecasting

Machine learning (ML) approach has proven to be an effective way in predicting the insect pest population, especially with the integration of climate variables of the pest environment and phenology of the host plant in the agriculture systems (Araújo et al., 2023). The combination of these ecological factors is ideal for the prediction of mango fruit fly in this context which is relevant in developing proactive pest control measures. Despite the contribution of traditional ecological models, Information Communication Technology have opened up more effective and efficient possibilities for agriculture pest and disease forecasting.

With the potential of ML techniques in improving the accuracy and responsiveness of insect pest and diseases, tools such as random forest, support vector machines and gradient boosting algorithms are capable of integrating diverse and complex datasets including plant phenology and climate variables such as temperature, rainfall etc. (Domingues et al., 2022). These methods are much improved with the ability to discover non-linear relationships, interactions and threshold dynamics that traditional linear models may fail to recognized. The ML approach has gain dominance in recent times in agroecological forecasting (Araújo et al., 2023; Domingues et al., 2022) thus most reliable and powerful than traditional regression models (Sikora et al., 2023).

These models are significant in developing early warning symptoms that are used to alert mango farmers and agriculture extension workers to mitigate risk potentials. The fruit fly forecasting helps stakeholders to implement adaptive management and control strategies, such as timely use of pheromone traps, the introduction of biological agents, or environmentally friendly pesticides (Reichstein et al., 2025).

Despite the technological improvement, there is a lacuna in the adjustment and validation of the predictive models especially in West African countries such as Ghana, where there exists a variation with other species in Asia and East Africa. Several studies in literature have explored predictions on climate variables or limited phenological indicators without taking cognizance of regional context (Choudhary et al., 2021a).

This particular study attempts to address the gap by adopting machine learning approach using python programming to develop a predictive model to ascertain the interaction of these climate variables, phenology and the population of the mango fruit fly in the Nadowli-Kaleo District of Ghana (Araújo et al., 2023). By integrating phenological field data with climate data, we aim to contribute to the development of site-specific, data-driven decision support tools that improve the resilience and productivity of mango farmers in the face of climate variability and pest infestation.

The combination of the various theories ie climate ecology theory, phenological theory and population dynamics theory provides an interdisciplinary and robust basis for analyzing the complex relationship between the seasonal climate variabilities, mango phenology and fruit fly population (Wacker 1998). These theories together provide opportunity to holistically understand how biotic and abiotic factors interact to influence the insect behavior and dispersals. The integrated approach enables the study to bridge the scientific gab between the study theories and practical applications by providing evidence-based solutions that can be adopted to address fluctuation in climate variables. Ultimately, the research aims to support mango farmers in Ghana with tools and insights that reduce the risks posed by climate-sensitive pests, thereby improving the sustainability and resilience of local mango production systems.

Conceptual Framework

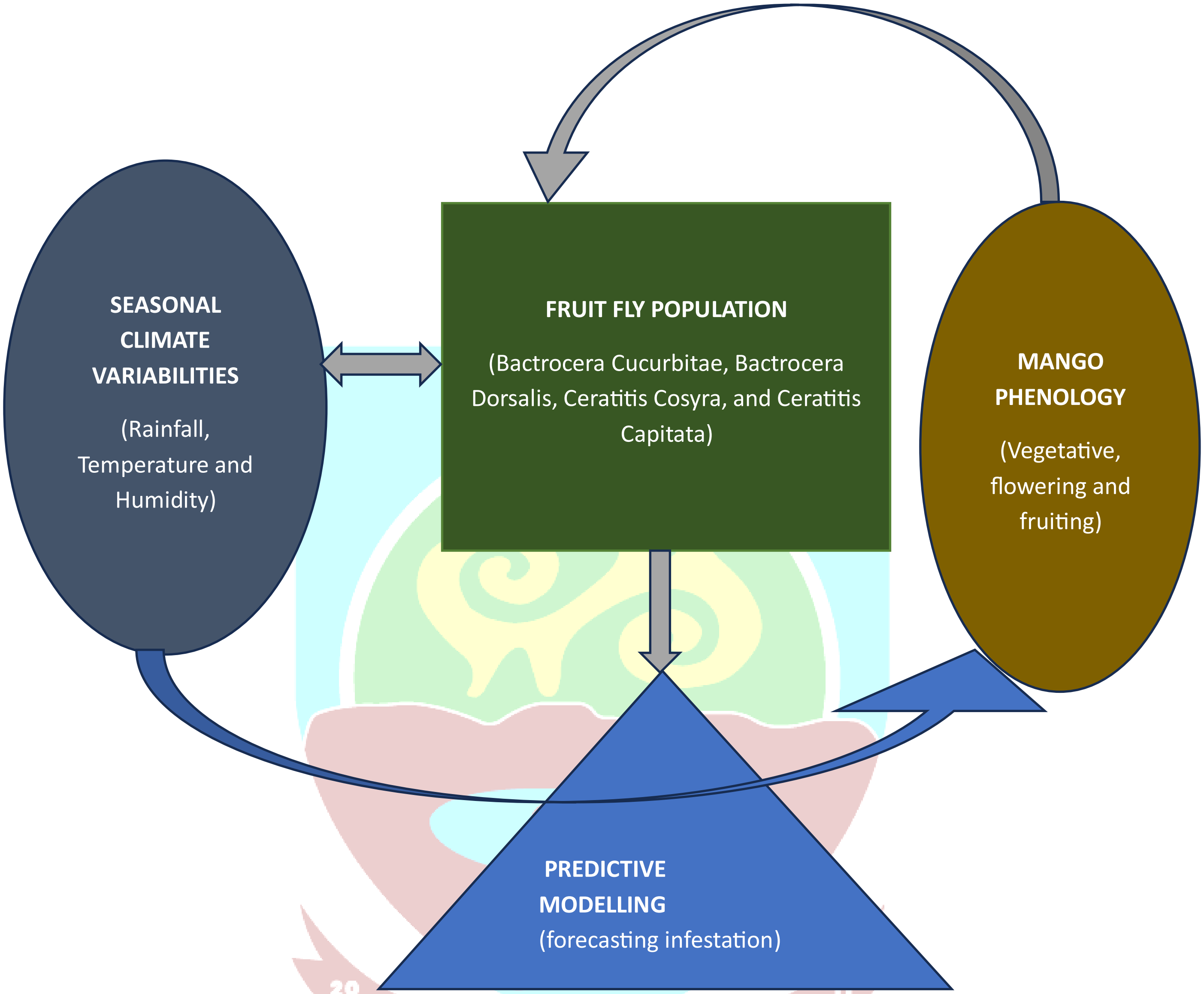


Figure 1: A conceptual framework of the study

Source: Author's construct (2025)

2.3 **Overview of mango production**

Mangifera indica is an extremely valuable tree fruit that thrives in various ecological zones and is recognized worldwide for its economic importance and also known as the 'king of fruits' (Tharanathan et al., 2006), mango has become an important agricultural product both on the local market and on export markets. The mango industry has shown promising prospects with increasing demand and growth potential (Evans et al., 2017). Nevertheless, mango production is often referred to as an important export commodity that has the potential to make a significant contribution to a country's foreign exchange earnings, comparable to other major export commodities such as cocoa (Hugo et al., 2021).

Despite these opportunities, the mango sector according to Opoku et al., (2025) faces production and export challenges, particularly due to pests such as the fruit fly species *Bactrocera invadens, Ceratitis cosyra,* etc. These pests and other factors have significantly hampered the marketing of mangoes and led to qualitative and quantitative problems, which have at times resulted in import bans on Ghanaian mango products. Although various measures have been taken to combat these problems, the industry continues to suffer from fruit fly, limiting its growth potential and market reach (Musah et al., 2014).

As a tropical and subtropical fruit plant, mango is widely cultivated for its economic and nutritional importance (Grechi et al., 2021). It thrives in various agroecological zones, particularly in regions with warm climates and distinct dry and rainy seasons (Hugo et al., 2021). The agronomy of mango is a multiple layer comprising the climate, soil conditions, propagation methods, management and harvesting techniques, these are all contributing factors to productivity and sustainable mango value chain enhancement. In terms of climatic requirements, the tree requires temperature of about 24 °C and 27 °C in the tropical and subtropical zones. However, the tree can tolerate temperature of about 45 °C for shorter periods (Sthapit et al., 2012; Lee et al., 2020). The mango tree is susceptible to frost and under such conditions causing severe damage to flowers and younger fruit sets (Durán et al., 2019). The mango tree strives well under moderate dry periods for better flowering and fruit formation with annual rainfall between 750mm to 2500 mm, a well-drained sandy loam soils with soil pH between 5.5-7.5 (Durán et al., 2019). Mango propagation is usually through grafting for early fruiting and genetic uniformity (Singh, 2018). For optimum yields, cultural practices and general farm management is recommended (Barbar et al., 2024).

The fruits are harvested at physiological maturity, which is characterized by size, shape and color (Abu et al., 2020). Just like many horticultural products, postharvest management is key to avoid loses (Asrey et al., 2023). To achieve a sustainable mango production, it is imperative to understand the phenology of the tree and associated factors that can affect its growth. (AntwiBoasiako et al., 2024). The phenology therefore refers to the sequence of developmental stages of the plant's life cycle, which are influenced by environmental factors such as rainfall, temperature etc. According to Antwi-Boasiako et al., (2024) there is a direct relationship between phenology and the population dynamics of the mango fruit fly where the fly becomes predominant at certain phenological stage. This is observed during the ripening stage where the fruit fly infestation is higher. These stages provide conducive atmosphere for reproduction and larval development (Narveh Awarikabey et al., 2023). Understanding the interaction of these factors is crucial for pest management and sustainable mango production.

2.3.1 Economic Importance of Mango

According to Hussain et al., (2021), the mango is referred to as 'king of fruits" due to it its great economic value at both local and global levels. The significance of the mango emanates from its role in addressing food security challenges to job creation, health, foreign exchange earnings and industrial usage (Yahia et al., 2023). Mango is of immense agricultural value in the tropical and subtropical economies including Ghana, regarded as an economic tree for livelihood improvement in rural areas.

Mango cultivation is an important source of income and a source of livelihood for smallholder farmers in Ghana (Yiran et al., 2023), hence the Nadowli-Kaleo is no exceptional. The tree's ability to thrive under diverse ecological conditions makes it ideal for both commercial and small-scale production and it is relatively lower in inputs requirements making the production economical for optimum yields since it's an important export commodity in the horticulture sector.

2.4 **Economic impact of fruit fly**

Fruit fly (*Diptera tephritidae*) is among the most damaging pest in the horticulture industry. The fly affect variety of crops especially mango, vegetables, Guava, Citrus etc. the specie *Bactrocera dorsalis* has been identified as one most distractive pest in Africa (Dominiak & Mapson, 2017; Opoku et al., 2025). Their economic loses transcends direct crop damage to post-harvest loses (PHL) and distractions, quarantine and trade restrictions (QTR) and increased cost of production (ICP) and pest management hence affecting famer's livelihoods (Arinloye etal., 2017; Ekesi et al., 2016). Understanding the economic impact of fruit fly is critical, particularly in region of Ghana where crops such as mango is of economic importance (Grechi et al., 2021).

Additionally, the fruit fly impacts have environmental and health implications, excessive use of pesticides is harmful to beneficial insects, soil and water contaminants and distraction of biodiversity. This however expose farmers and consumers to high risk as result of pesticides residuals and unregulated environmental activities.

2.4.1 Direct and indirect production losses

The fruit fly is one insect with the fastest reproduction cycle; within 2-3 weeks the flies go through a complete metamorphosis. Considering the shortest reproductive cycle, it causes significant loses before and after harvest by laying eggs in the fruit and the larva feeds on the fleshy fruits affecting the fruits quality (Sarker et al., 2009). This singular feeding habit of the larva causes decay and reduces the aesthetic quality and quantity of the fruit's yields. According to Lee et al., (2020), the rate of damage can range between 30% - 100% depending on the level of infestations. This percentage losses are more detrimental to smallholder farmers who are highly dependent on the crop for livelihood. That notwithstanding, fruit fly infestation requires intensive measures which increases production cost unlike other pest control (Nankinga et al., 2014). The over reliance of synthetic pesticides control also leads to environmental and health consequences (Sarker et al., 2009; Mulungu et al., 2023).

Although farmers may resort to Integrated Pest Management techniques (IPM), the cost of pheromone traps and other sophisticated methods may be unfriendly especially to smallholder farmers with low-income levels even though the IPM techniques are sustainable ways of pest control and environmental stewardship (Antwi-Boasiako et al., 2024a).

2.4.2 Trade restrictions and export losses

The infestation of fruit fly on export horticultural commodities have caused a several quarantine concerns resulting in the restriction and infested products and banning of some export countries from the international markets (Opoku et al., 2025). For countries such as Ghana, that exports a lot of mango products, compliance to safety standards and certifications are crucial to protecting the country's horticultural market integrity and ensuring farmers gains. The cost involved in the process of certification, pre-shipment and fumigations to main and improve the quality standards of the produce all contributes to producer burdens thus affecting marginal profits.

2.4.3 Post-harvest losses and impacts on rural livelihoods

Infestation of fruit fly is not limited at the field, due to the oviposition processes of the insect fly, eggs deposited in the fruit are transported outside the filed settings to continue life process. The larva that feeds on the fleshy fruits continue to damage the products especially the mango fruits. This singular act of the flies affects the entire value chain and causing significant loses (Nankinga et al., 2014). This has been a major factor affecting the potentials of the mango industry and the entire horticulture value chain especially in the rural economy (Choudhary et al., 2021).

According to Niassy et al. (2022), the fruit fly has become a global challenge largely affected by smallholder farmers. At the micro economic levels, household food securities are threatened, low-income levels affect health and education thus contributing to perpetual poverty in rural communities. The lower profits encountered by famers as a result of fruit fly effects and additional cost, discourages investment in the mango industry thereby reducing the potentials of the horticulture industry (Evans et al., 2017).

2.4.5 Policy and research gaps.

Despite the economic impacts pose by mango fruit fly, limited literature on the nexus between the population dynamics and climate variables especially in Ghana exacerbate the challenges (Narveh Awarikabey et al., 2023). To address this menace, it requires investment in scientific research, extension service delivery and capacity building for farmers (Kruger, 2016).

A holistic understanding of these concepts and adequate scientific knowledge will enhance sustainable pest control methods and ecosystem safety.

2.5 **Growth stages and life cycle of the fruit fly.**

Just like many other insects, the mango fruit fly undergoes a complete metamorphosis (Manrakhan, 2024). The life cycle of the fly comprises four different stages; the egg stage, larva, pupa and adult fly stage. The egg stage begins the life cycle of the fly after the female lay’s eggs beneath the fruit of the mango (Manrakhan, 2024). Using its ovipositors, the fruit fly can lay between 2-10 eggs on the skin of the fruits that penetrates through smaller holes. Depending on favorable environmental conditions, such as high temperatures and high humidity, the incubation period is within 1-3 days. Fruits that are infested by the eggs have small dark spots on the fruits indicating a clear sign of early infestation (Huang et al., 2020b).

After hatching, the larva produced feeds on the fruit flesh for survival. This stage is one of the most destructive stages of the fly’s infestation, as the larva bore holes into the fruit causing internal rot and tissue malfunctioning. The larval stage takes approximately one to two weeks (7-14) days to develop into a pupa. The infected fruits fall prematurely with soft and discolored areas. This causes significant economic and production loses. According to Huang et al., (2020) and Manrakhan, (2024), they both suggested that this stage is largely influenced by the degree of ripe fruits amidst favorable temperature and humidity.

After the larva has fully developed, it leaves the fruit and burrow into the soil to pupate (Manrakhan, 2024). The pupa is protected with a hard case formed from the larval skin and depending on the prevailing environmental conditions the stage takes 6-10 days. Under cooler and drier conditions, the pupal stage may prolong allowing the fruit fly to survive (Huang et al., 2020b). Whiles pupation occurs in soils, it exposes the pupa to soil-dwelling predators (Sarwar et al., 2014).

Once the pupa is grown, it develops into the fly. The fly emerges from the pupal case to begin another life process of reproduction. Adult fly is sexually matured within a period of 8-12 days and can live for several weeks to months under favorable environmental conditions (Manrakhan, 2024; Sarwar et al., 2014). The adult fly feed on the plant's nectar and fruit juice, whiles the female flies search for protein sources for egg maturation. This stage is the critical point for reproduction and population growth of the fruit fly as females can lay hundreds of eggs during their lifetime. The season and availability of host fruits provide optimal conditions for the egg laying thus increasing the intensity of the fruit fly emergence.

2.6 Species of Fruit fly

The Mango fruit fly belongs to the family *Tephritidae,* with different kind of species that causes damage to fruits and vegetables. Some of these species are crop or plants specific and are of specific geographic origins. However, other species of the family *Tephritidae* are common to many ecological zones. Among these, several species are attracted to the mango, causing significant damages. Notable among these is the *Bactrocera and ceratitis* being the common genera (Ekesi et al., 2016) Aside the physical damages caused by fruit fly, they are also of quarantine concerns thereby restricting the export and import of horticulture products across the global market systems (Evans et al., 2017). Among the numerous fruit fly species, the most common that attack the mango is the *Bactrocera dorsalis* also referred to as the Asian fruit fly (Yonow et al., 2004; Michel et al., 2021a). It spread across different countries in Asia, African and other Tropical and sub-tropical regions. Despite the fact that mango is the preferred host, the fly also attacks guava, citrus, banana and other fruits. The *Bactrocera dorsalis* is considered the most destructive fruit fly pest of the mango, causing a lot of damage and losses before and after harvest. This is possible because the *Bactrocera dorsalis* strives across different climatic conditions with a shorter reproductive life cycle.

Another specie of economic concern is the *Bactrocera zonata,* commonly known as the Peach fruit fly. This particular specie is mainly found in areas around south Asia, Middle \east and some parts of Africa. The Bactrocera zonata also attacks several fruit crops and vegetables including mango. Although less widespread than the *Bactrocera dorsalis*, it is also a dangerous specie to mango, particularly in the regions where it co-exists with the environmental factors.

Aside the *Bactrocera dorsalis* and *Zonata,* one other species of concern is the *Ceratitis coysra,* also known as the marula fruit fly. *Ceratitis coysra* is a native of the sub-Sahara Africa. This specie attacks mangoes, marula and other fruits of similar family. But in Africa, it attacks only mangoes especially at the ripening stages. Other species that causes economic loses to mango fruits include; *Ceratitis capitata, Anastrepha spp Dacus spp* and most of these species are found in Africa, Asia, Europe and America (Choudhary et al., 2021a).

Understanding the diversity of this fruit fly is important because it poses several challenges to mango cultivation due to their distinct preferences to host plant, reproductive cycles and response to varied environmental conditions. However, species such as *Bactrocera dorsalis and Ceratitis* are of particular concern due to their high infestation rate and ability to survive under diversified ecological conditions (Antwi-Boasiako et al., 2024; Narveh Awarikabey et al., 2023).

2.7 **Climate of Ghana and the Upper West Region**

Ghana is predominantly a tropical climate characterized by distinct rainfall patterns of both wet and dry seasons. The seasons are largely determined by the interactions of the Intertropical Convergence Zone and the Harmattan winds (Bessah et al., 2022). Ecologically, Ghana is subdivided into five main climate zones; the Guinea savannah zone, Sudan savannah, coastal zone, the transition zone and the forest zone (Yamba et al., 2023). The average rainfall in Ghana varies between 800mm and 900mm in the Sudan savannah and coastal zones, whiles the forest zone records averagely 1900mm, mostly the high average rainfall observations. In the Guinea savannah zone, the average rainfall is around 1100mm. both seasonal and annual rainfall are subjected to spatial and temporal variations across the country hence the increasing with decreasing latitudes from north to south determines the both seasonal and annual rainfall reliability in the country.

Average temperatures vary about 25.5 °C in the southwestern coastal parts and about 30°C in the Northern belt of the country. Rainfall in the southern parts is bimodal between March -July and September – November, and unimodal in the northern parts from May to October (Yamba et al., 2023). The annual rainfalls in the country ranges between 800mm and 2000mm in the Northern and Southern zones respectively (Aryee et al., 2018).

Higher temperatures are recorded throughout the year, between 24 °C and 35 °C, with relative humidity varying between 60% and 90% subject to the season and location (Bessah et al., 2022).

2.8 Types of climate variability

According to Asare-Nuamah & Botchway (2019), climate variability is referred to the shortterm seasonal changes to long-term shifts in climatic conditions at different time scales. these fluctuations are caused by both natural and anthropogenic factors. Climate variabilities are of different types and forms which include but not limited to; Seasonal variabilities, inter-annual variabilities, decadal variabilities, etc.

Seasonal climate variability refers to the changes that occur at regular intervals in the course of the year as a result of the earth's position relative to the sun. this type of variability is common in regions with distinct wet and dry seasons. Yamba et al. (2023), observed that the rainfall in Ghana varies throughout the country with the wet season favoring plant growth whiles dry seasons affects water availability. Fluctuations in temperature especially between day and night across the season also affect plant growth and development. Such as flowering and fruiting (Antwi-Boasiako et al., 2024).

Inter-annual variability is another type of climate variability that occurs from year to year (Mauget & Upchurch, 1999). This particular variability is believed to have significant impacts on agriculture productivity since the yearly variations are influenced by large scale phenomenon such as El Niño and La Niña effects.

Decadal variability also refers to a longer-term fluctuation in climatic conditions that occurs over a period usually 10-20 years (Latif & Keenlyside, 2011). These changes are not easily predictable but poses a significant impact on agriculture and ecosystem biodiversity, these include; the types of crops cultivated, the crop development stages, and rate of pest infestation.

Climate variability occasioned by North Atlantic Oscillation (NAO) or pacific decadal Oscillation influences the weather elements over a long time periods which affects rainfall distribution and extreme temperatures (Hurrell & Deser, 2009), in effect influences plant phenology and pest population dynamics.

2.9 The combined interactions of climate variability, mango phenology, and fruit fly

Mango Phenology refers to sequential growth stages of the life cycle of the mango plant. These stages include the vegetative, flowering, fruiting and ripening stages of the plant. According to Antwi-Boasiako et al. (2024), the phenological stages are very responsive to climatic factors such as temperature, rainfall and relative humidity as well as photoperiodism.

Evans et al. (2017), posited that, temperature ranges between 24 °C and 30 °C is essential for flowering and fruiting of the mango. Prolong exposure to high temperatures especially above 35°C leads to heat stress resulting in wilting and flower drop, poor fruits formation and general reduction in quality (Choudhary, et al., 2021b). On the contrary, lower temperatures at the flowering stage delays anthesis, incomplete pollination etc. which is translated to lower yields (Borghi et al., 2019). Extreme temperature fluctuations also increase the susceptibility of mango tree pest and diseases further reducing productivity.

Nonetheless, rainfall also have a significant influence at various growth stages of the mango. Pathogens and other pest of mango are rampant especially during excessive rains. This is common during flowering and fruiting where fungal infection etc. are on the ascendency (Lawson & Rands, 2019). Relative Humidity (RH) which is another important climate variable also influences the mango physiological processes as well the infestation of pest and pathogens in the orchard (Anagha et al., 2024). High RH promotes the development of fungal pathogens particularly during flowering and fruit development (Broufas et al., 2009; Anagha et al., 2024). On the other side, lower humidity can inhibit transpiration which may lead to water stress and affects photosynthesis, which in turn reduce yield.

Antwi-Boasiako et al. (2024), observed that the combination of rainfall, temperature and humidity further exacerbates the impacts of climate variabilities on mango production. It was observed that when high temperatures combined with low rainfall and high humid conditions, it facilitates drought. Also, high humid conditions with excessive rainfall also creates conducive avenue for pest and diseases. Several studies pointed to the effects of climatic variabilities especially fluctuating climate conditions such as temperature, rainfall and humidity on the influence of Mango fruit fly (Bana et al., 2017; Choudhary, et al., 2021a). The variation in these conditions affects reproductive capacities, survival and the general biological process of pest. Whiles extreme temperature accelerates the multiplication of fruit flies, lower temperature below 15°C inhibits oviposition and larval development (Domingues et al., 2022; Narveh Awarikabey et al., 2023).

Additionally, erratic and irregular rainfall patterns affect the fruit fly population by distorting the host environment (Szyniszewska et al., 2020). Higher rainfall during fruit set formation is observed to create a conducive microclimate which favors larval development (Choudhary, et al., 2021b). This therefore implies that RH is a critical factor for the biological activity of fruit fly (Broufas et al., 2009).

Despite the role of climate variabilities of the population dynamics of the fruit fly, the mango phenology also plays a role in the availability and distribution of the mango fruit fly pest. The interaction of fruit fly pest activity and the phenology is critical in assessing fruit crop damages and economic losses (Narveh Awarikabey et al., 2023). During certain phenological stages such as flowering, it creates conditions for the activities of adult fly for later infestation at the fruiting stage (Grechi et al., 2021; Narveh Awarikabey et al., 2023). This is necessitated by the increased sugar contents and low acidity during the biochemical process which attracts more of adult fly especially for egg laying (Grechi et al., 2021; Domingues et al., 2022). Post harvest activities leading to the presence of overripe and waste fruits further complicate the issues by providing breeding grounds for the fruit flies (Megha et al., 2023).

CHAPTER THREE

RESEARCH METHODOLOGY AND MATERIALS

3.1 The Study Area

The study was conducted at the Matco Mango plantation in the Nadowli-Kaleo District of the Upper West Region. The research site is the largest mango plantation in the district with a plot size of about 50 acres, occupied by different varieties of mango including Kent, Kaits and Brooks. The district just like many areas in the savannah ecology is characterized by tropical climatic conditions with distinct wet and dry seasons. This variation in climatic conditions provides an ideal setting for the study. The orchard was selected for the study based on its land area, the presence of different mango species, and its accessibility for collecting relevant data.

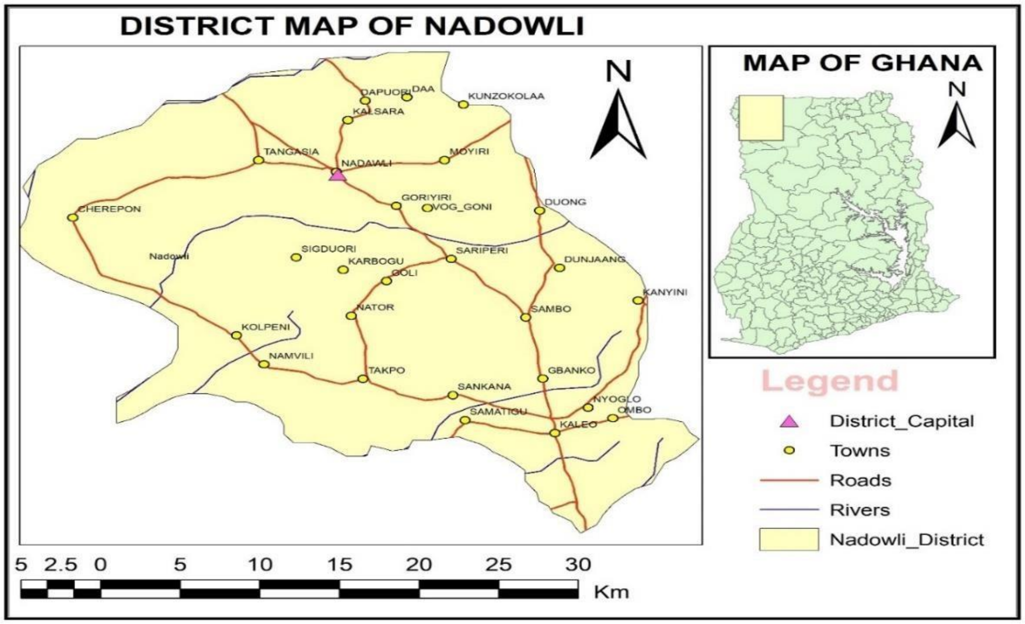


Figure 2: The map of the study area at left showing Ghana as a country at the top right. **Source: Author's construct (2025)**

3.2 Philosophical and methodological paradigm

This study primarily focuses on the pragmatic philosophical paradigm, which highlights the practical use of knowledge and combines various methodological approaches to address complex, real-world problems (Brister 2023). The research also draws on the post-positivist paradigm, particularly in the use of empirical data, statistical modelling and objective measurements(Allmendinger 2002), to investigate the relationships between climate variability, mango phenology and population dynamics of *Diptera tephritidae.*

3.3 The Research Design

The influence of seasonal climate variabilities and mango phenology on the population dynamics of the mango fruit fly were studied in the Nadowli-Kaleo District. Longitudinal studies were employed. This enabled the gathering of past and present data over time. The data collected between 2022 and mid-2025 were used for the study. Representing four mango production seasons. To assess seasonal variations in mango tree phenology, climate variables, and fruit fly populations, a randomized complete block design (RCBD) was adopted for the field layout to establish monitoring blocks within the orchard. A plot size of 10 m^2 was used for each block, containing four different lures (baits). Each bait has a unique target species of *Diptera tephritidae* with a total of sixteen (16) pheromone traps. The pheromone traps are monitored and catches recorded at 10 days of regular intervals to determine the pest population. Secondary data was sourced at end of May 2025 at 5:00pm GMT from the Ghana Meteorological Agency (GMet). This comprises climatic data of key variables for the study such as temperature, rainfall, and relative humidity.

Data analysis involved correlations to determine the direct and linear relationships between environmental factors such as temperature, rainfall and humidity as climatic factors of the study with respect to the population of specific fruit flies. An analysis of variance test was conducted to assess the differences in mean fruit fly population across the mango phenology. Multiple linear regression (MLR) model was used to combine all these factors to confirm the inadequacies of the simple linear regression. Moreover, Seasonal Harmonic Analysis (SHA) was performed to decompose the seasonal and inter-annual variability, strong and regular seasonal pattern and the residuals over a four-year trend. A generalized linear model (GLM) was used to analyze the interaction between phenological stages and climatic conditions in predicting fruit fly infestations, and, finally, a random forest regressor (RFR) model was used to predict fruit fly populations. The model was trained on data from 2022 to 2024 and then tested to predict the fly count for the entire 2025.

3.4 Research Approach

The author adopted quantitative research approach for the study. This was applicable and necessary based on the nature of data required for the study. The entire field data on fruit fly counts at various phenological stages, and the climatic data from GMet were purely numeric data, hence the choice of quantitative approach. In a quantitative study, validity and reliability are assured when the researcher adopts the right tools and design for the study (Heale & Twycross, 2015).

3.5 Sampling Methods

The appropriate sampling method for the study is a combination of purposive and systematic random sampling. Purposive sampling was necessary because the site selected for the study is the largest mango plantation within the study or geographical area, which also constituted different mango varieties including Kents, Kaits and Brooks. Etikan (2016) suggested that the choice of a purposive or convenience sampling technique is largely dependent on the nature and type of the research; hence, the need to adopt a purposive technique for this study, given its nature and the study demands. Whereas systematic random sampling was adopted for its practical convenience (Mostafa & Ahmad, 2018).

The farms selected for the study was chosen based on specific criteria relevant to the research objectives. These criteria include: Location within the Nadowli-Kaleo District, history of mango cultivation and known instances of mango fruit fly infestation and the presence of mango trees at various phenological stages. Campbell et al., (2020) posited that purposive sampling has a long-standing developmental history, simple and straightforward and is better matching to the research objectives. The sampling technique ensures that the orchard selected for the study provides meaningful insights into how climatic and phenological factors influence fruit fly populations.

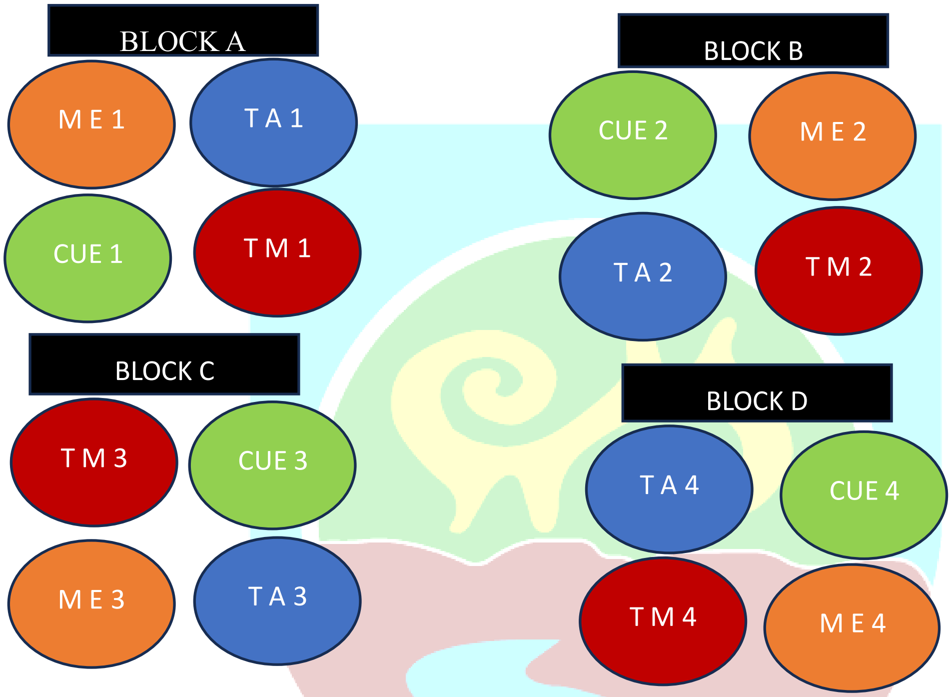
3.5.1 Systematic Random Sampling (Tree sampling)

Once the farms have been selected through purposive sampling, systematic random sampling was used to choose individual mango trees for observation and data collection. According to Mostafa & Ahmad, (2018) systematic sampling is easier and can provide more precise estimators than simple random sampling especially when the selection of the sample units is done in the field study. A fixed interval approach was applied for tree sampling, where every tree in a row stands the chance of being selected for phenological monitoring and fruit fly population assessment.

This combined sampling approach ensures that the study focuses on farms and trees relevant to the research objectives while allowing for randomization to minimize selection bias and increase the representativeness of the data.

Together, this design and sampling method provided comprehensive and reliable data to address the study’s objectives, allowing for reliable conclusions on the influence of climate and mango phenology on mango fruit fly population dynamics.

FIELD LAYOUT



KEY

Methly Eugenol	🟠
Terpinyl acetate	🔵
Cuelure	🟢
Trimedlure	🔴

Figure 3: RCBD field layout in the orchard. *Scale:* $10\times10\ m^2$

3.5.2 Phenological Stage Monitoring

Mango trees in the selected farms were monitored during flowering stage, small fruit size stage, large fruit size stage and vegetative stage as key phenological stages for the study purpose. Observations were made on every single stage for the detection of the availability and presence of fruit flies. This was a routine practice in every ten days in the morning hours of the day and three observations in every month and the stages were categorized based on visual inspection of the trees' development.

3.5.3 Mango Fruit fly Population Monitoring

The fruit fly population were monitored using baited traps and direct fruit inspection methods. The RCBD was set up for fruit fly and each trap contains a bait of a specific fruit fly specie on the respective mango trees. Four different Pheromone Traps (PT) was placed at each block with a total of four different blocks within the orchard, and counts of fruit flies were recorded within ten (10) days interval. Data on different fruit fly species were recorded separately for easy analysis.

3.6 Research materials

For the research work, various materials are essential for attracting, capturing, and preserving the fruit fly. These materials were carefully selected based on purpose.

The process begins with the setting of a pheromone trap on the selected trees. Each trap contains bait targeting a specific fly specie and a DDVP killer agent. The pheromones in each trap include Methyl Eugenol (ME), Cur lure (CUE), Terphenyl Acetate (TA), and TriMed lure (TM). These are hanged on different trees in each block. This was done for all of the sixteen (16) pheromone traps that were used for the four (4) different blocks. Each trap container is labeled according to the initials of the bait and the block number. For instance; TM 1, ME 2, CUE 3, TA 4 etc.

Once the fruit fly is attracted to the traps, a DDVP (Dichlorvos) agent is employed to kill them, preventing their escape. The fly is caught up in the trap containers, which are designed to house the pheromones and DDVP while also containing the captured specimens.

Afterward, the catches are transferred into vials for collection. These vials serve to hold the catches for later examination; they are stored in the vails, labeled and preserved for further examination and verifications. The fruit fly catches are stored and preserved using bio-ethanol to ensure their condition is maintained for further identification and analysis.

This carefully organized setup ensures the effective collection, preservation, and study of the insect pest.

Table 1: Categories of baits and targeted fruit fly species

S/N	**Name Of Pheromone**	**Target Species**
1.	Cue lure	*Bactrocera cucurbitae*
2.	Methyl Eugenol	*Bactrocera dorsalis*
3.	Terphenyl Acetate	*Ceratitis cosyra*
4.	TriMed lure	*Ceratitis capitata*

3.7 Data collection methods

This outlines the sources of data and the procedures carried out in gathering the relevant data for the study. The data for the entire study is purely quantitative data. Basically, the study relied on two sets of data. Both primary and secondary data sources were identified to achieve the general aim of the study. The Secondary data were sourced from the Ghana Meteorological Agency (GMet) in the Upper West Region which included climate variables such as temperature, rainfall and relative humidity, whiles primary data were collected by the researcher which focused on fruit fly population counts trends and observations of the mango phenological development.

3.7.1 Primary Data Collection

Data on fruit fly were primarily gathered through field monitoring using baited traps. Data collection took place between 2022 to mid-2025 of the mango production seasons to assess the presence and prevalence of different fruit fly species. This was achieved by using various pheromones as baits which was targeted at specific fruit fly species. This, which helped attract and captured the fruit fly for identification and analysis. The pheromone traps were set in blocks of four (4) with different types of lures targeting four different fruit fly species such as *Bactrocera cucurbitae, Bactrocera dorsalis, Ceratitis cosyra and Ceratitis capitata*. The traps were labeled according to the type of bait used and the tree number in each block. (figure 3).

With a total of sixteen (16) pheromones, the traps are closely monitored and recordings are taken in every ten (10) days interval to observe the population trends and figures are counted and recorded using a self-designed template.

As part of the primary data collection, the phenological data of mango trees were collected through field surveys, observations, and recordings. The key phenological stages observed and recorded for the purposes of the study included the Vegetative stage, Flowering stage, small fruit stage, and large fruit stage. The trees are equally labeled according to the block eg. BLK A; T1, T2, T3 and T4. BLK B T1, T2, ………T4 etc.

3.7.2 Secondary Data Collection

The study relied on secondary sources to gather relevant data in support of the research objectives. Seasonal Climatic data for the study, including weather elements such as temperature, relative humidity, and rainfall were obtained. The data covered a period of four

(4) mango production seasons between 2022-2025 of which the various elements were recorded on daily basis corresponding to the study period. These records were sourced from the Ghana Meteorological service station in Wa, located in the Upper West Region.

3.8 Data Analysis and Presentation

The data was integrated and prepared according to the objectives of the study. The datasets on fruit fly count from four types of baits and daily weather data (Temperature, Rainfall and relative humidity) were cleaned and aggregated to a consistent monthly frequency. This master dataset was then enriched with historical daily humidity data for the region to create a more complete environmental context. To ensure the integrity and reliability of the prediction model, the dataset was filtered to include only complete historical data from January 2022 to December 2024. For the target variable selection, the analysis focused on predicting the population for the mid-season of 2025 of fruit fly attracted to the baits, as these showed the most significant response to environmental factors in our preliminary analysis.

A modelling approach that involves a Python programming, version 3.x (PSF) USA, specifically random forest, was used to predict fruit fly populations. The primary models and analyses included: Correlation analysis for the assessment of direct linear relationships between all environmental variables and specific fruit fly populations. Seasonal Harmonic decomposition enabled the isolation of the underlying trend, seasonal patterns and random fluctuations within the fruit fly population, and predictive modelling (random forest regression model). The model was trained to predict the monthly population of fruit fly species on climate, phenology and seasonal-based characteristics.

The whole analysis involved a General linear model, which was used for the broad set of analysis. The Seasonal Harmonic Analysis was employed to track changes in populations across seasons, The relationship between Mango Phenological and Mango Fruit fly Population Dynamics, was analyzed using Linear correlation analysis to determine if and how fruit fly populations fluctuate with the phenological stages of the mango tree. A one-way ANOVA tests were conducted to compare the mean of fruit fly population across different mango phenological stages (vegetative, flowering, small fruits, and large fruits).

Lastly, generalized linear model (GLM) made it possible to satisfy conditions in Predicting fruit fly Infestation, combining the effects of mango phenology and climatic variables on the fruit fly populations. Random forest regressor predictive modeling was trained to forecast the population of the fruit fly and counts for the year 2025. This was able to identify which phenological stage and climatic conditions can best predict the likelihood of fruit fly infestations and how the key variables influence one another.

The analyzed data were presented in tables, graphs and charts to illustrate the findings of the study. This is necessary for easy comprehension.

3.9 Ethical Considerations

The site selection for the study was conducted in collaboration with Matco farms ensuring that their consent is obtained before conducting the study. Their confidentiality was assured since all information gathered was used solely for academic purposes and potential conflicts of interest were declared throughout the research process and originality of the study was assured.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 The seasonal climatic variations and population of the fruit fly

This section discusses the population dynamics of various fruit fly species in relation to seasonal climate changes. The data includes both historical and recent information from 2022 through mid-2025. The study used a 12-month calendar year, from January to December, to define each season. The tree's phenology was categorized into the following stages: vegetative, flowering, small fruit size, large fruit size, and mature fruit size (appendix I for interpretation). These phenological stages were assigned and monitored based on key variables such as temperature, rainfall, and humidity for each season. These factors were analyzed alongside the population dynamics of the flies at each phenological stage. The data was presented in charts for easier understanding. However, the results showed different outcomes across seasons regarding population dynamics and their interactions with climatic factors.

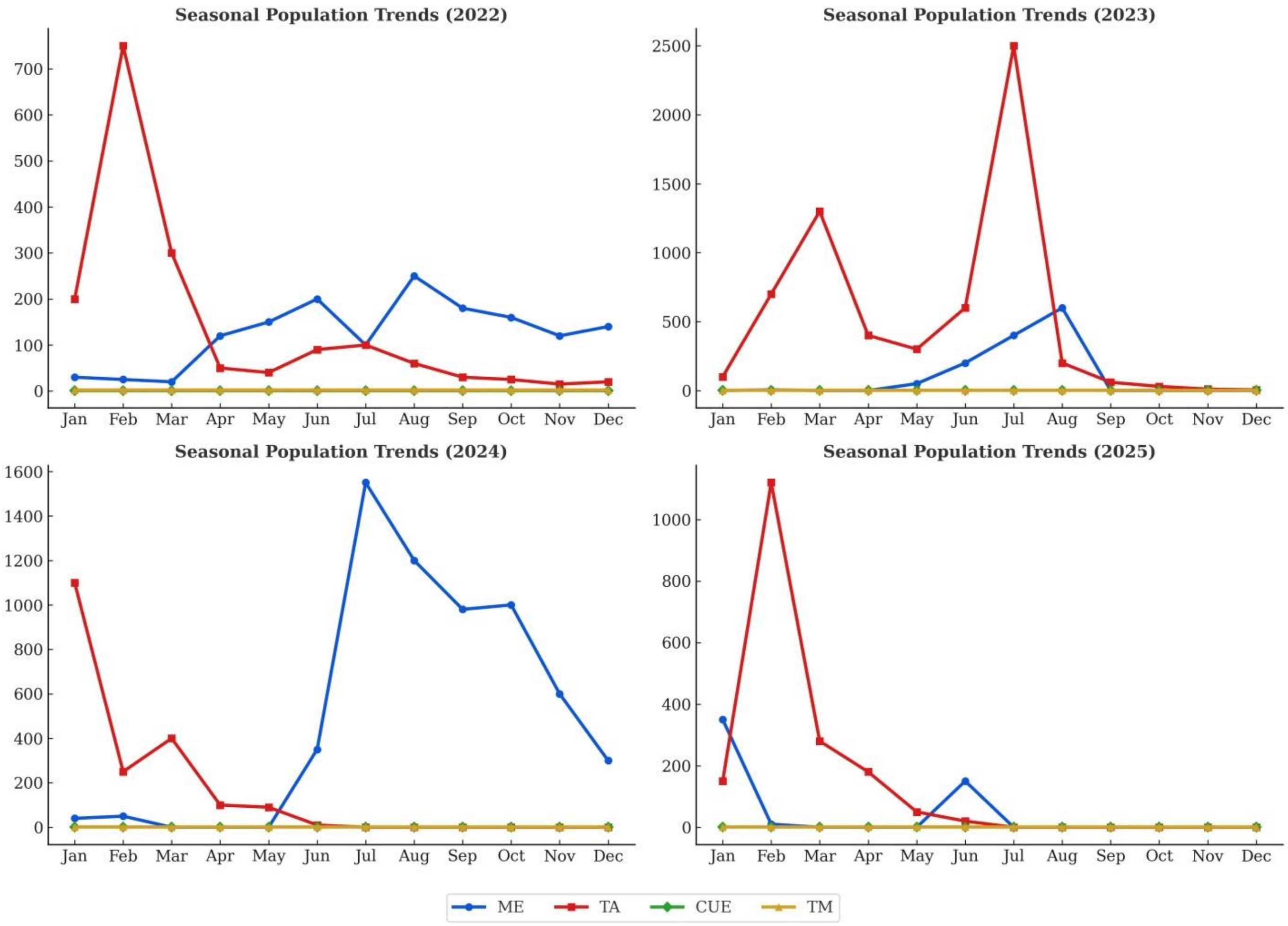


Figure 4: Seasonal climatic variabilities on fruit fly population dynamics (2022-2025)

(ME-Methyl eugenol, TA-* **Terphenyl Acetate** *CUE-cue lure, TM-TriMed lure) *Source: Authors field report (2025)*

In the year 2022, from Figure 4: The bait, Terphenyl Acetate which targets *Ceratitis cosyra*, a particular species of the fruit fly, shows dominance from January 2022 to March 2022, with a downward trend in April to June in the same year, then a steady rise in July. The Terphenyl Acetate declined again from August through the end of the season in December. Methyl eugenol, a bait that is targeted at *Bactrocera dorsalis* shows a fluctuating trend with significant presence throughout the 2022 season and demonstrated a surge from April to December 2022. However, the highest fly population for the season was recorded in January for *Ceratitis Cosyra* (Figure 4).

In the year 2023, the presence of Methyl eugenol (*Bactrocera dorsalis*) was observed only between April and September, whereas Terphenyl Acetate (*Ceratitis cosyra*) dominated from January to December, showing a significant surge of flies from June to August. Unlike 2022, when the highest count was recorded in January. This data was further analyzed in subsequent sections to identify factors influencing the change from the previous season, as there has been a dramatic shift in monthly populations between 2022 and 2023. These drivers of seasonal changes in the fruit fly populations were examined in relation to climatic factors through simple to multiple regression analyses.

In the year 2024, there was a sharp contrast between the dominance of different fruit fly species. It was clearly divided between Methyl Eugenol (*Bactrocera dorsalis*) and Terphenyl Acetate (*Ceratitis cosyra*). While Terphenyl Acetate was more prevalent from January to July, Methyl Eugenol only appeared from January to March and became completely negligible in April. A significant rise in population was recorded in June, with numbers declining from August to December in that particular season of 2024. The results in the year 2023 illustrates that *Ceratitis cosyra* is only prevalent during the first and second quarters of the year: January, February, and

March (JFM): and April, May, and June (AMJ). These periods in the Guinea Savannah ecological zones are characterized by dry conditions and higher temperatures, while *Bactrocera dorsalis* only appears during the last two quarters July, August and September to October, November and December (JAS–OND), with some rainfall and high humidity. This situation warrants further statistically analysis the correlation between these climatic factors and the fruit fly populations.

The year 2025, seasonal population data were only observed from January to June it shows a similar trend like 2022 where the two main baits (Terphenyl Acetate and Methyl eugenol) demonstrated presence from the beginning of the season from January. However, Terphenyl Acetate recorded the highest dominance over Methyl Eugenol.

The four seasons observed for the study period showed some similarities, with little distinction in outlook, considering the months that showed the presence of the fly, as well as the months that recorded peak levels of the various species. This clearly shows that there has been a seasonal variation in the population dynamics of the fruit fly species during the study period (Figure 4). Generally, the two other baits, the Cue lure (*Bactrocera cucurbitae*) and TriMed lure (*Ceratitis capitata*) shows insignificant appearance throughout the study period. It was however concluded that there is no presence of *Bactrocera cucurbitae* and *Ceratitis capitata* species in the study location.

Once figures 4: presented a much-confused outcome in understanding the seasonal trends of the general fruit fly population, a combination of the past and present seasonal data trends that were observed for the period between 2022-2025, the data was further investigated on a preliminary analysis considering the nature of short-term data available. The fruit fly population over time immediately highlights a pronounced seasonal rhythm. This affirms the notion that climate variations such as temperature fluctuations between day and night or between seasons can affect plant growth, flowering, and fruiting in plants such as mango (Antwi-Boasiako et al., 2024). To further investigate and isolate these patterns, a Seasonal Harmonic Analysis (SHA) was performed to decompose the population trend into three components: a long-term trend, a strong and regular seasonal pattern, and residuals (random noise). With that, seasonality is the most dominant feature of the data, suggesting that any successful predictive model must account for the time of year. Figure 5: clearly shows recurring peaks and troughs in the fruit fly population, indicating that the time of year is a critical factor.

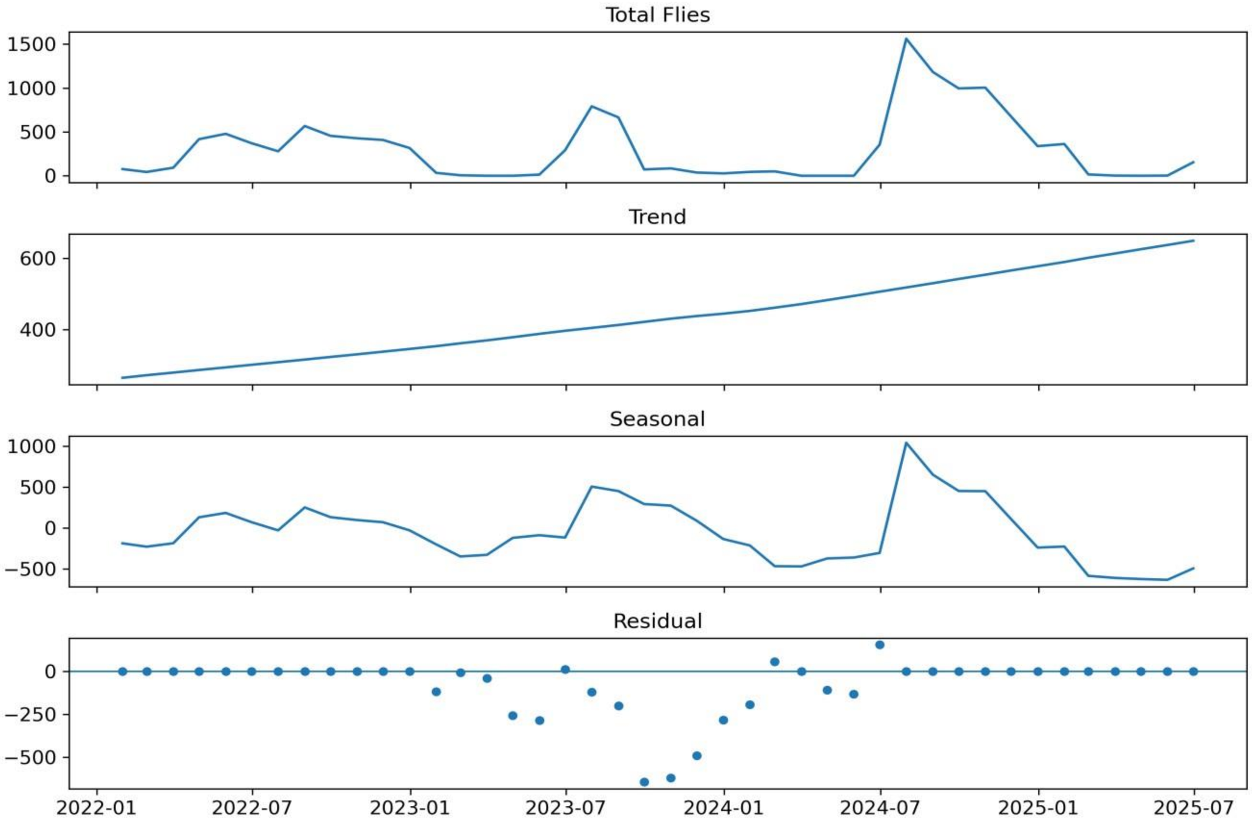


Figure 5: A four Seasonal Harmonic Decomposition of Fruit Fly (Trend, Seasonality, Residuals)

4.2 Relationship between fruit fly population and the phenological stages of Mango

The fruit fly's population which was determined by the availability and presence of the fly catches, were related to the various growth stages of the Mango. Relationships that existed between the phenological stages and the population were observed and presented in charts.

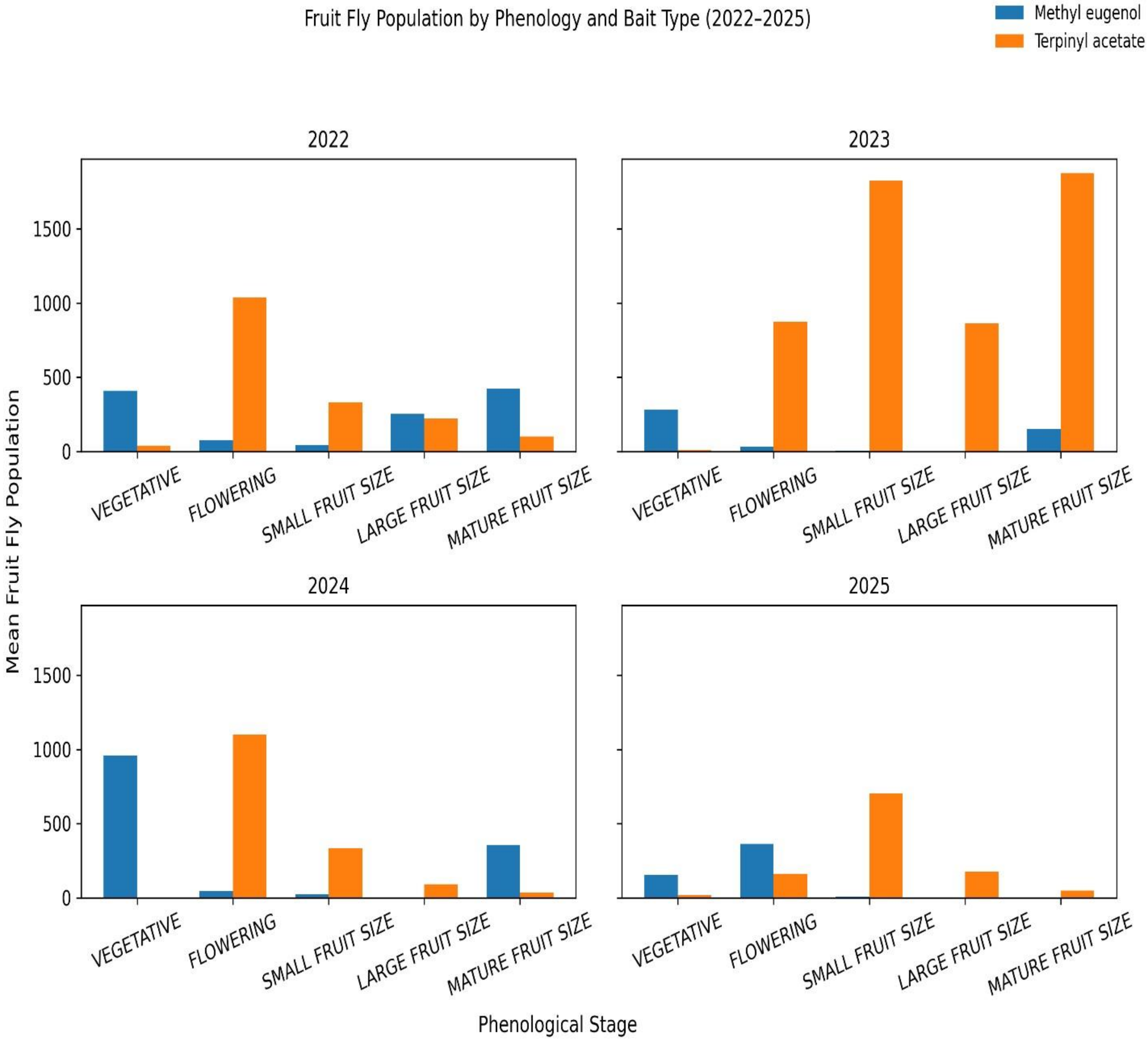


Figure 6: Influence of Phenology on fruit fly population (2022-2025)

Source: Author's field report (2025)

Figure 6: represents the population dynamics of the fruit fly species for the year 2022-2025 at various stages of the mango development. In the year 2022, it was observed that at the vegetative stage, Methyl Eugenol recorded the highest peak of fruit fly catches. Terphenyl Acetate recorded its highest number of catches during the flowering stage and the lowest during the large fruit stages. The results demonstrated that the species *Bactrocera dorsalis* runs through all the various phenological stages but very negligible during the small fruits stage and are most prevalent during the vegetative stage. *Ceratitis Cosyra* that was also prevalent at all the phenological stages shows insignificant numbers during the large fruit and mature fruit stages. Interestingly*, Bactrocera Cucurbitae and Ceratitis capitata* were conspicuously missing throughout in the 2022 season. this is so telling that the *Bactrocera Cucurbitae* and *Ceratitis capitata* are uncommon species within the study area.

The year 2023 presents different outlook as compared to the 2022 results. It was observed that Methyl eugenol only recorded values during the vegetative, mature fruits and flowering. Whiles Terphenyl Acetate recorded values across all the different phenological stages with the highest value during the mature fruit stage. However, Methyl eugenol still maintained its highest value during the vegetative stage confirming the population prevalence of *Bactrocera dorsalis* specie at the vegetative growth stages. However, zero values were recorded for Cue lure and TriMed lure as it was observed in the year 2022 season also confirming no availability of *Bactrocera cucurbitae* and *Ceratitis capitata.*

The year 2024 just like the previous years, Methyl eugenol shows high prevalence during the vegetative stage and some appearance during the flowering and small fruit stages. With the exception of the vegetative stage, Terphenyl Acetate demonstrated presence at all other stages with its highest value during the flowering stage. The lowest for Terphenyl Acetate was also recorded during the large fruit stage. Similarly to the previous years. Cue lure and Trimed lure were very negligible.

Data for the year 2025 was collected for January to June which represented the phenology of flowering, large fruits, Mature fruits and small fruits stages with the exception of Vegetative stage as shown in figure 6: This provides opportunity for predicting future occurrences. Meanwhile, the results obtained shows a similar trend in the population dynamics of the various fly population. Terphenyl Acetate shows appearance across the different stages of growth with a strong appearance during the small fruits stage and lowest during the mature fruit stages.

Whiles vegetative stages were not captured during this particular season, it was evident that Methyl eugenol values were recorded at the flowering stages and small fruits stages, From the historical data for 2022 to 2024, the 2025 trend shows a high possibility of recording Methyl eugenol values during the vegetative stage for the season.

It is widely postulated that, *Bactrocera dorsalis* and *Ceratitis coysra* are among the most destructive pests in fruit production worldwide (Dominiak & Mapson, 2017; Opoku et al., 2025). This particular study agrees strongly to that assertion since it was generally observed from this study that the most dominant species in the study area were *Bactrocera dorsalis* and *Ceratitis coysra.* As it was recorded by Methyl eugenol and Terphenyl acetate respectively. However, Terphenyl Acetate shows availability in almost every growth stage but mostly common during the fruiting periods of the Mango phenology. Although *Bactrocera dorsalis* were recorded but Methyl eugenol shows presence at the various growth stages of the Mango, it was commonly observed during the vegetative stages. It can therefore be concluded that *Bactrocera cucurbitae* and *Ceratitis capitata* were uncommon fruit fly species in the

NadwoliKaleo District. The study did not discover a contrary view in that regard since Antwi-Boasiako et al., (2024) and Narveh Awarikabey et al., (2023) observed that *Bactrocera dorsalis* and *Ceratitis Coysra* are of particular importance in Africa including Ghana of which the study location is not exceptional due to their high infestation rates. However, the best time to target the two common species (*Bactrocera Dorsalis and Ceratitis coysra*) for pest management and control was identified to be at the peak seasons; i.e. the fruiting stages.

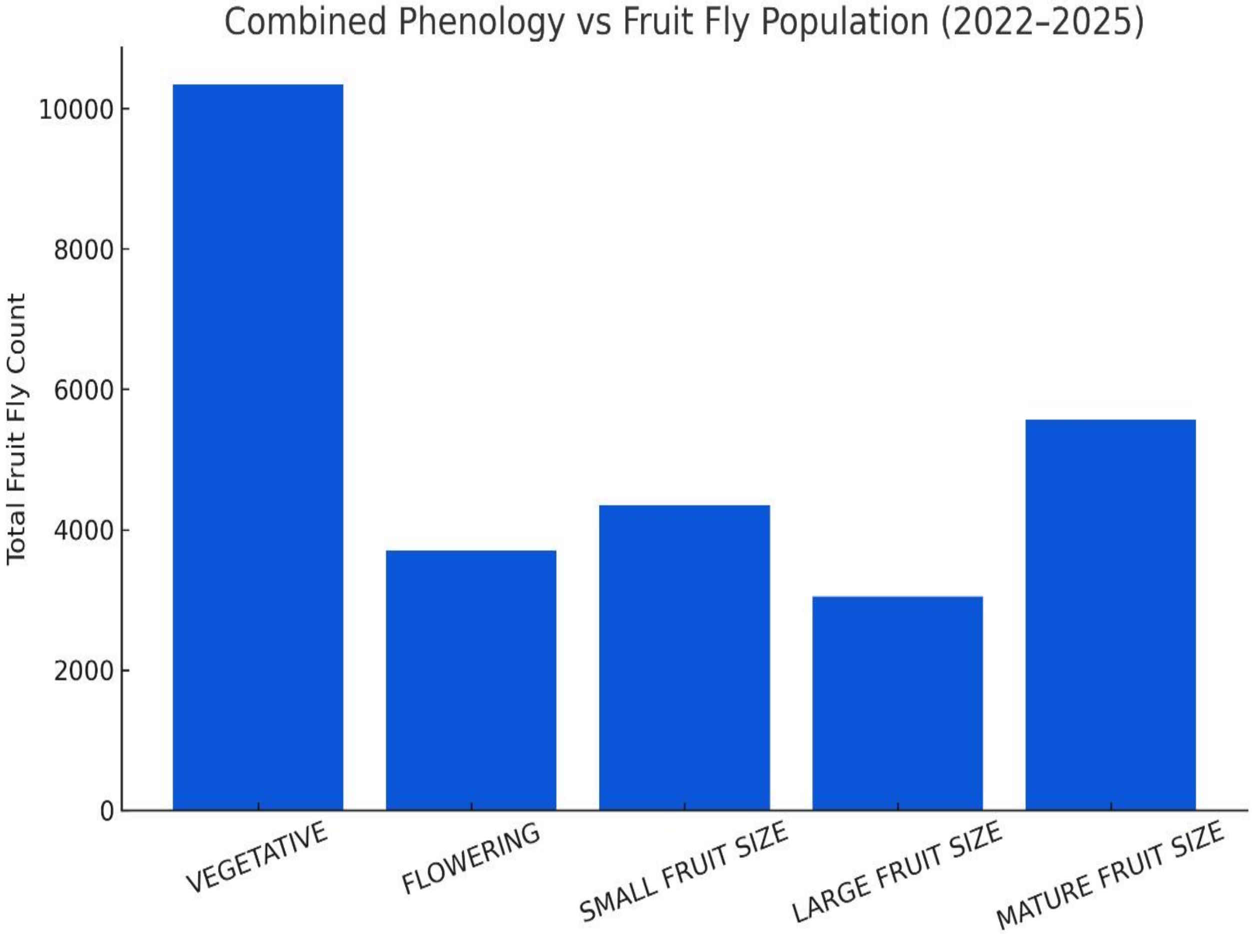


Figure 7: Composite Chart for phenology and fruit fly for 2022-2025

Source: Author’s field report (2025)

4.3 Combined interaction between climatic factors, phenology and fruit fly population dynamics

The data was analyzed to ascertain the interaction between the key variables of the study. Firstly, the study analyzed the direct relationship between climatic factors and the phenology of the mango. From the year 2022-2024, min temperatures were consistently high around 34°C which favours fruit set development and also attractive for fruit fly host. Relative humidity values of about 66% are within the optimal ranges that supports adult fruit fly survival and reproductive cycles of the fruit fly. A decrease in rainfall and relative humidity therefore affects fruit fly outbreaks whereas warm temperatures and high rainfall enhance large fruit set development and most likely a high fruit fly pressure. This impact of the climate variables on the respective growth stages of the tree crop and how that influences the population of the fruit fly is critical phenomenon. With regards to that, a direct linear relationship was conducted on the key factors; which includes the phenology, climate variables and the population of the fruit fly (Table 3). This was conducted using Pearsons's correlation to assess the direct relationship of all variables. The results indicated that, the linear correlations between total fruit fly count, phenology, and climate variables are generally weak. However, a moderate positive correlation with climatic factors and the population of the fruit fly were observed. This provided a background for Sthapit et al. (2012); Lee et al. (2020) that the fluctuations of climate factors such as temperature variations, rainfall, and humidity, have been shown to affect the life cycles and reproductive patterns of organisms including the fruit fly.

According to Choudhary et al., (2021a), during key stages of fruiting and ripening, mango trees create optimal conditions for fruit fly reproduction and infestation this result has a contrary opinion since phenology and total fruit fly population has been negatively correlated. Narveh Awarikabey et al. (2023) posited that the phenological stages of the mango have a direct impact on the population dynamics of pests such as the mango fruit fly which has refuted the claim of this study hence the need to further explore the relationship beyond simple linear models.

Table 2: Linear correlation between fruit fly, phenology and climate variables.

Variable	Total_Flies	encoded phenology	Mean_Max_Temp	Mean_Min_Temp	Total_Rainfall_mm
Total_Flies	1	-0.1	0.22	0.17	0.16
Combined phenology	-0.1	1	0.23	0.2	0.36
MeanMax_Temp	0.22	0.23	1	0.82	0.24
Mean_Min_Temp	0.17	0.2	0.82	1	0.27
Total_Rainfall_mm	0.16	0.36	0.24	0.27	1

(mean values of climatic factors can be viewed from Table 5-7 at appendix)

Total_Flies = Represents the total number of fruit flies captured from the pheromone traps

Mean_Max_Temp = The average daily maximum temperature during the data collection

Mean_Min_Temp= The average daily minimum temperature during the data collection

Total_Rainfall (mm) = The rainfall data recorded in millimeters for the study period.

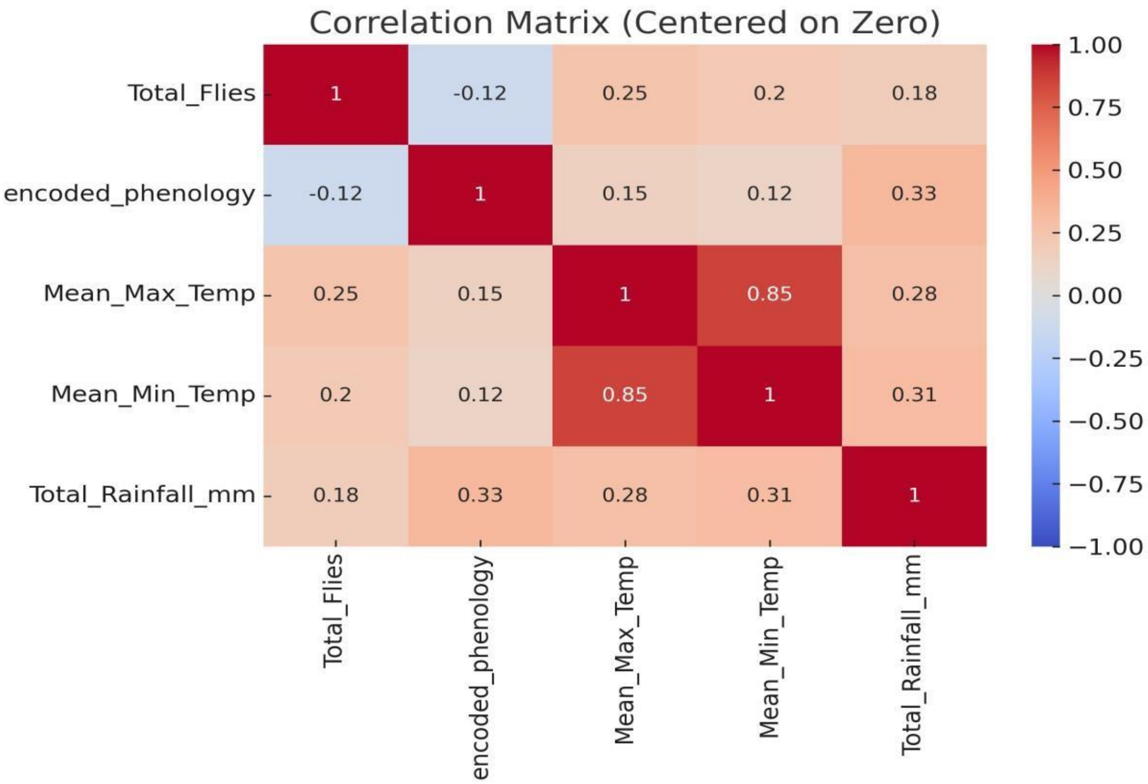


Figure 8: Pearson Correlation Matrix of Key Variables

Source: Author's field report (2025)

4.3.1 Direct Relationships of complete data set

A correlation analysis of the complete dataset was conducted and the results showed a direct influence of each climate variable on the key fruit fly populations as posited by Narveh

Awarikabey et al. (2023). From the results, the total monthly rainfall shows a moderate positive correlation (0.41), specifically with the methyl eugenol (*Bactrocera dorsalis*) population. This indicates that higher rainfall is associated with an increase in this specific fly. This finding affirms the claim that rainy seasons, increases the fecundity and longevity of adult fruit flies (Broufas et al., 2009).The effects on the other fruit fly specie are negligible.

While Anagha et al. (2024) claimed that temperature is a decisive factor for the development, reproduction, and survival of the mango fruit fly, the optimal temperature range for its activity is typically between 20°C and 30 °C. The study has observed that temperature is negatively correlated. Which means that higher Temperatures reduces fruit fly infestation and the vice versa. In the study, the minimum temperature (min_temp) exhibits a notable negative correlation of (− 0.57) with methyl eugenol (*Bactrocera dorsalis*) counts. The influence of maximum temperature on a month-to-month basis appears to be less direct for all fruit fly species.

With regards to relative humidity (RH), the relationship between average monthly humidity and all fly populations is weak (0.11). This indicates that total monthly rainfall is the most influential direct climate driver for the fruit fly population dataset, specifically *Bactrocera dorsalis.*

The table 3: shows a linear correlation between *Diptera tephritidae* species baited by Terphenyl Acetate, Methyl Eugenol, Cue lure and TriMed lure with the climatic variables (rainfall, max and min temperature as well as relative humidity). The key findings however, demonstrated that; rainfall as a climate variable exhibited a moderate positive correlation (r = 0.41) with the methyl eugenol (*Bactrocera dorsalis)* population. Whiles the minimum temperature shows a moderate negative correlation (−0.57). this therefore suggested that months with lower minimum temperatures accounts for higher fly counts. This affirms the claims of Sthapit et al., (2012); Lee et al., (2020)that the fluctuations of climate factors such as temperature variations, rainfall, and humidity, have been shown to affect the life cycles and reproductive patterns of organisms including the fruit fly pest.

With regards to phenology, the distribution of fruit fly populations across the different phenological stages have shown that, there are visible differences, meanwhile the significant overlap between the phenological stages suggests that phenology alone is not a straightforward predictor of the fruit fly population. Whereas extant literature suggested that during key stages of fruiting and ripening, mango trees which are characteristics of the phenology, create optimal conditions for fruit fly reproduction and infestation (Choudhary et al., 2021).

Table 3: Linear correlation between climate variables and fruit fly counts

Variable	**r-value**	**p-value**	**Significance**
Phenology (encoded)	-0.44	0.004	**
Temperature Max	-0.21	0.182	Ns
Temperature Min	-0.57	0.001	***
Rainfall (mm)	0.41	0.007	**
Relative Humidity	0.11	0.488	Ns

***Indicates highly significant, **strongly significant, *moderate significant and Ns shows none significant statistical value. (mean values of climatic factors can be viewed from Table 5 – 7 at appendix).

Furthermore, a One-Way ANOVA test was conducted to determine if the mean fruit fly population differed across phenological stages. The resulting p value of 0.488 is well above the significance threshold of ≤ 0.05. This confirms that phenology is not a statistically significant predictor of the average fruit fly population. The overlapping distributions in Figure 16 visualize this lack of a clear distinction.

4.5 Multiple Linear Regression model

To further investigate the combined influence of the key ecological and climatic variables on fruit fly populations, a Multiple Linear Regression (MLR) model was first created. This model included all relevant predictors such as mango phenology, temperature, humidity and rainfall in a linear framework to test their collective explanatory power. However, the results of the MLR analysis revealed a fundamental limitation; the model did not provide statistically significant results. In particular, the Prob (F-statistic) was 0.403**, meaning that the model did not explain a substantial proportion of the variance in the fruit fly populations. In other words, the linear combination of predictor variables failed to adequately capture the complexity or structure of the underlying ecological processes. This non-significant result highlights the insufficiency of a simple linear modelling approach in contexts where nonlinear interactions and synergistic effects are likely.

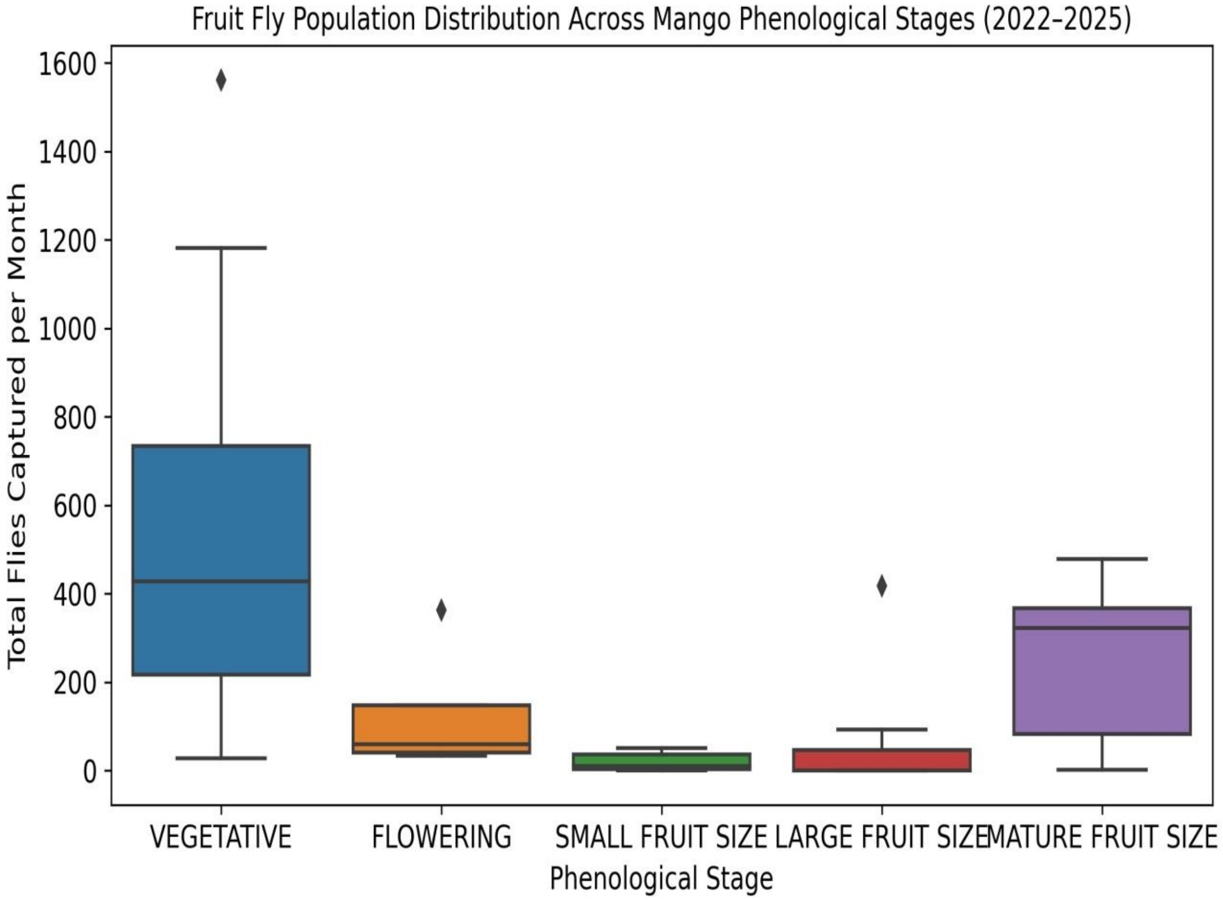


Figure 9: ***Distribution of Fruit Fly Populations by Mango Phenological Stage (Refer appendix I for phenology interpretation)***

The fruit fly population distribution shows the presence of the insect throughout all phenological stages of the tree crop life. The fly count during the large fruit stage was less than all other phenological stages. The most prevalence of the fruit fly count were during the small fruit size, vegetative and flowering stages as shown in figure 16. However, from the box plots It was observed that, during large fruit size stages, there was unusual fruit fly count indicating a very high capture. A spike in fruit fly activity was also observed at the vegetative stage which was higher than normal and a high outlier reflecting unusual large capture with the typical monthly values during the small fruit stages. This was different for the small fruit size stage with a low value suggesting a month with much fewer value.

4.6 Generalized Linear Model analysis of the Interaction of key variables

Once simple statistical models could not delve into complex relationships of the data variables, a more robust analytical approach was required. Hence the need to adopt a Generalized Linear model (GLM) to better account for non-linear relationships and the interactive effects between the climatic variables and other ecological factors. The GLM was appropriate for its flexibility in analyzing different types of responses and ability to model interactions between predictors. This allows space for a nuanced understanding of the factors affecting the fruit fly population.

The results of the GLM, as provided in Table 5, constitute one of the most critical findings in the entire dataset. The model identified that mean maximum temperatures (MMT) have a highly significant influence on the phenology of mango, represented in the model as ‘encoded phenology’ ‘Mean_Max_Temperature’, with a p-value of approximately 0.000, indicating a very strong statistical relationship between temperature and phenology. This means that when certain phenological stages coincide with higher temperatures, fruit fly population density also increases. This assertion aligns with existing research that temperature is a decisive factor for the overall development, growth, reproduction, and survival of the mango fruit fly (Anagha et al., 2024).

In practice, this result means that neither the phenology of the mango nor the temperature alone fully explains the variability of fruit fly abundance. Rather, it is the combined influence of these two variables e.g. certain phenological stages coinciding with higher temperatures that significantly influences fruit fly prevalence. As indicated by Antwi-Boasiako et al., (2024), Mango as a tropical fruit is very sensitive to climatic conditions that directly affect its growth, flowering, fruit formation and yield quality.

This result emphasizes the importance of considering both biological undertones of the mango tree and the seasonal climate patterns in the prediction and control of fruit fly outbreaks as grounded in the systems ecological framework of the study theories.

Moreover, it also confirms the use of the GLM approach in uncovering complex ecological interactions that could not be recognized with simpler models. A similar was recommended by Gutierrez et al., (2021) that in order to meet this ongoing challenge in prediction fruit fly population and activities, “investment is needed to collect sound biological data and develop mechanistic models to predict the geographic range and relative abundance of these and other invasive species, and to provide a scientific basis for eradication measures.”

This finding means that the effect of temperature is not constant; it depends entirely on the plant's life stage. For example, high temperatures may accelerate fruit fly development and population growth primarily when mature fruit is available (a specific phenological stage), but have a negligible impact at different times, hence rainfall has no discernible effect.

Table 4: Regression analysis using Generalized Linear Model (GLM) with Interactions of fruit fly population, and climatic variables.

Term	Coefficient	Std. Error	Z-value	P>|z| (Sig.)
Intercept	6.154	0.038	161.318	0 (***)
encoded_phenology × Mean_Max_Temp	0.007	0.001	7.884	0 (***)
encoded_phenology × Total_Rainfall_mm	2.65e-05	7.67e-05	0.345	0.73 (ns)

*** represents highly significant, **strongly significant, *moderate significant and, ns indicates non-significant values at p 0.05 level (mean values of climatic factors can be viewed from Table 5 – 7 at appendix)

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATION

5.1 Summary of key findings

This study aimed to understand the population dynamics of mango fruit flies in the NadowliKaleo District of Ghana by analyzing the influence of climatic variation, mango phenology, and their interactions on the prevalence of key fruit fly species. It was guided by three specific

research objectives, using a combination of statistical modeling and seasonal decomposition/harmonic analysis to investigate both linear and nonlinear relationships and identify the key ecological and climatic predictors of fruit fly outbreaks.

The results clearly indicate a strong seasonal pattern in the fruit fly population. A seasonal decomposition analysis revealed recurring peaks and troughs in the fruit fly population, especially in relation to the annual climate cycle. The results made it evident that climatic variabilities influence the fruit fly population trends. For instance, total monthly rainfall and minimum temperatures were the main determinants. Rainfall, in particular, showed a moderate positive correlation with the fruit fly population (r = 0.41), while minimum temperature demonstrated a moderate negative correlation (r = -0.57). The findings, however, suggested that variation in climatic conditions, especially during the rainy season and cooler months, significantly influences the fruit fly population.

Further examination of the relationship between phenology and the fruit fly population revealed that at certain stages of phenology, such as fruiting, there was a positive correlation with *Ceratitis coysra.* The vegetative stages, however, were strongly associated with a high incidence of Bactrocera dorsalis. Although the results of the phenology and fruit fly population, using a linear correlation model, were generally weak, this suggests that phenology alone is not a strong predictor, even though certain phenological stages are linked to higher fruit fly abundance. The recurrence of different fruit fly species at various phenological stages indicates that other variables must be considered alongside phenology to reach a conclusion. This demonstrates that the influence of phenological stages on fruit fly populations heavily depends on specific climate variables, such as high temperatures. In practice, certain mango development stages coinciding with elevated temperatures significantly impact the timing and severity of fruit fly populations. Meanwhile, this interactive effect was not captured by simpler models, such as MLR, which produced non-significant results (Prob F = 0.403), underscoring the need for non-linear and interaction-based modeling approaches in such ecological studies.

Furthermore, with regards to the four bait types tested, only Methyl eugenol and Terphenyl Acetate traps consistently captured fruit fly species, suggesting that *Bactrocera dorsalis* and *Ceratitis cosyra* are the predominant species in this district. Only insignificant numbers were caught with the Cue lure (*Bactrocera cucurbitae*) and the Trimed lure *(Ceratitis capitata),* indicating that these species are not widespread in the study area.

5.2 Conclusions

Based on the study, the results revealed a clear seasonal pattern in the fruit fly population, with recurring peaks and troughs. Climatic factors such as rainfall and minimum temperature ranges between 22^0C – 25^0C were identified as the most significant variables influencing fruit fly population dynamics, especially for *Bactrocera dorsalis.*

The distribution of fruit fly populations across the different phenological stages have shown that, there are visible variations. However, the most prevalence of the fruit fly count was during the small fruit size stage, this could be linked to the high susceptibility of small fruits to the insect oviposition and pest -host synchrony. It was generally observed from this study that the most dominant species in the study area were *Bactrocera dorsalis* and *Ceratitis coysra.* this could be linked to favorable microclimatic conditions (Temperature and Humidity). The presence of outliners across the stages indicated the fruit fly persist all year round. Meanwhile, low counts during large and mature fruits stage could be attributed to partial resistance and increased farmer inventions (harvesting and sanitation),

Based on the final objective of the study that delved into the combined interactive effects of all variables, it was revealed that the phenology of the mango alone was insufficient as a predictor, but when combined with climatic variables, particularly temperature above 30 ^{0}C, that has a positive interaction coefficient of 0.0072 per °C enhances phenological effect hence becomes a strong determinant of fruit fly abundance.

Furthermore, the population dynamics of the fruit fly in the Nadowli-Kaleo district are not driven by simple linear relationships but by a complex interaction of ecological timing and climate variation. The infestations are mainly influenced by the season, underscoring the need for timely pest monitoring and control.

The fruit fly species *Bactrocera dorsalis* and *Ceratitis cosyra* are the most common in the district, and control measures should be focused on their peak periods, which are expected to align with the vegetative and fruiting stages, respectively.

5.3 **Recommendations**

The study strongly recommends farmers to leverage on available and innovative communication channels to understand climate and weather situations for the adoption of good agronomic practices that will minimize the influx or insurgence of the harmful economic insect.

It also recommends further research into the mango fruit fly's reproductive cycle, focusing on seasonal and climatic variations, and using the findings of this study to guide predictions. This will help determine the specific seasons of fecundity, fertility, and ovipositing, as well as the impact of climatic factors on these processes. Ultimately, the findings emphasize that for the successful implementation of integrated pest management strategies (IPMS), it is important to focus on seasonal phenology, climate forecasts, and species-specific behaviors to sustainably control mango fruit fly populations in the region.

Finally, the study recommends analyzing a long-term dataset that includes additional environmental or spatial variables to enhance prediction accuracy and reliability of the model, as its current data was limited to a short (four-season) training period. Additionally, the Random Forest model can be retrained and is very likely to become a powerful and precise tool for proactively predicting high-risk periods for fruit fly infestations, enabling more targeted and efficient pest management.

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APPENDICES

Appendix I: Fruit Fly Data Collection Tool

Name of farm: MATCO MANGO PLANTATION **Location:** JANG

District: NADOWLI-KALEO **Region:** UPPER WEST

Name of data collector: ……………………………………………………

Status of farm at the time of data collection: Vegetative, [✓ Flowering,] small fruit, large fruit, Mature fruit

Date: ………………………………. (D/M/Y)

ME - Methyl eugenol	**CUE – Curelure**	**TA - Terphenyl Acetate**	**TM - Trimedlure**
T1 = Other =	T1 = Other =	T1 = Other =	T1 = Other =
T2 = Other =	T2 = Other =	T2 = Other =	T2 = Other =
T3 = Other	T3 = Other =	T3 = Other =	T3 = Other =
T4 = Other =	T4 = Other =	T4 = Other =	T4 = Other =
Total (Fruit flies) = Total (Other) =	Total (Fruit flies) = Total (Other) =	Total (Fruit flies) = Total (Other) =	Total (Fruit flies) = Total (Other) =

Note:

Vegetative= No visible signs of flowers or fruits till the appearance of first set of flowers

Flowering= visible sign of first 2-3 flowers

Small fruit = fruit size less than the size of lawn tennis ball

Large fruit = fruit size bigger than the size of lawn tennis ball

Mature fruit = fruits ready for harvest

Appendix II: Picture gallery

Plate 1: Researcher monitoring pheromone traps at the field

Plate 2: Researcher setting up pheromone traps with baits and DDV killer agents

Plate 1: Pheromone traps with fruit fly catches

Plate 2: State of orchard at Matco mango plantation

Appendix III: Mean minimum and maximum values of climatic factors for the study period (2022-2025)

Table 5: Overview of the mean values of temperatures that influenced population of mango fruit fly at Nadowli-kaleo District of Ghana.

	Mean values of Temperature (^{0}C) ***(Values from June 2025 to December 2025 were forecast values)***							
	2022		2023		2024		2025	
Months	Min	Max	Min	Max	Min	Max	Min	Max
Jan	17.54	34.46	20.74	35.83	20.28	35.57	19.52	35.29

Feb	23.86	36.49	21.65	36.39	20.66	35.09	22.06	35.99
Mar	24.42	36.25	23.01	36.36	22.73	36.17	23.39	36.26
Apr	24.44	34.65	22.77	35.92	22.30	35.82	23.17	35.46
May	22.66	34.04	22.22	34.04	21.74	34.15	22.21	34.08
Jun	22.45	32.08	21.58	32.40	21.15	32.38	***21.73***	***32.29***
Jul	22.33	31.29	21.48	32.43	20.38	32.32	***21.40***	***32.01***
Aug	22.31	30.99	21.23	31.81	20.16	31.25	***21.23***	***31.35***
Sep	22.32	31.59	21.34	33.31	19.11	33.27	***20.92***	***32.72***
Oct	21.88	34.57	22.05	34.49	21.81	34.61	***21.91***	***34.56***
Nov	21.99	35.26	21.82	35.73	21.66	35.86	***21.82***	***35.62***
Dec	20.55	34.18	19.20	35.49	18.86	35.39	***19.54***	***35.02***

January (Jan), February (Feb), March (Mar), April (Apr), May (May), June (Jun), July (Jul), August (Aug), September (Sep), October (Oct), November (Nov), December (Dec), Minimum (Min), Maximum (Max)

Table 6: Overview of the mean values of rainfall (mm) that influenced population of mango fruit fly at Nadowli-kaleo District of Ghana.

	Mean values of Rainfall (mm) ***(Values from June 2025 to December 2025 were forecast values)***							
Months	2022		2023		2024		2025	
	Min	Max	Min	Max	Min	Max	Min	Max
Jan	57.1	57.1	32.0	32.0	0.0	0.0	29.7	29.7
Feb	85.8	85.8	95.0	95.0	10.2	10.2	63.7	63.7
Mar	22.2	22.2	32.9	32.9	41.3	41.3	32.1	32.1
Apr	59.0	59.0	122.8	122.8	64.6	64.6	82.1	82.1
May	145.9	145.9	137.2	137.2	46.3	46.3	116.5	116.5

Jun	94.9	94.9	128.5	128.5	159.3	159.3	***127.1***	***127.1***
Jul	166.0	166.0	246.2	246.2	66.4	66.4	***159.5***	***159.5***
Aug	213.8	213.8	97.9	97.9	346.7	346.7	***189.5***	***189.5***
Sep	209.6	209.6	200.3	200.3	183.8	183.8	***197.9***	***197.9***
Oct	12.0	12.0	27.3	27.3	37.5	37.5	***26.6***	***26.6***
Nov	36.9	36.9	16.1	16.1	36.8	36.8	***29.9***	***29.9***
Dec	153.9	153.9	58.8	58.8	21.7	21.7	***97.5***	***97.5***

January (Jan), February (Feb), March (Mar), April (Apr), May (May), June (Jun), July (Jul), August (Aug), September (Sep), October (Oct), November (Nov), December (Dec), Minimum (Min), Maximum (Max)

(Data for rainfall was based on single observation hence the similarity in mean minmum and maximum values)

Table 7: Overview of the mean values of Relative humidity that influenced population of mango fruit fly at Nadowli-kaleo District of Ghana.

Months	Mean values of Relative Humidity (%) ***(Values from June 2025 to December 2025 were forecast values)***							
	2022		2023		2024		2025	
	Min	Max	Min	Max	Min	Max	Min	Max
Jan	67.1	67.1	66.2	66.2	65.8	65.8	66.4	66.4
Feb	66.9	66.9	66.1	66.1	65.9	65.9	66.3	66.3
Mar	66.5	66.5	65.9	65.9	66.0	66.0	66.1	66.1
Apr	66.8	66.8	66.7	66.7	66.4	66.4	66.6	66.6

May	67.4	67.4	67.2	67.2	66.7	66.7	67.1	67.1
Jun	67.9	67.9	67.6	67.6	67.6	67.6	***67.7***	***67.7***
Jul	68.3	68.3	68.0	68.0	67.8	67.8	***68.0***	***68.0***
Aug	68.6	68.6	67.8	67.8	68.4	68.4	***68.3***	***68.3***
Sep	68.1	68.1	67.5	67.5	67.9	67.9	***67.8***	***67.8***
Oct	66.4	66.4	66.3	66.3	66.5	66.5	***66.4***	***66.4***
Nov	66.2	66.2	66.0	66.0	66.2	66.2	***66.1***	***66.1***
Dec	66.9	66.9	66.4	66.4	66.0	66.0	***66.4***	***66.4***

January (Jan), February (Feb), March (Mar), April (Apr), May (May), June (Jun), July (Jul), August (Aug), September (Sep), October (Oct), November (Nov), December (Dec), Minimum (Min), Maximum (Max)

(Data for relative humidity was based on single observation hence the similarity in mean minimum and maximum values)