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Abstract

Climatic parameters including rainfall, temperature, relative humidity, and solar radiation affect phenology of shade trees. This study investigated effects of climatic parameters on litterfall of five shade trees (*Milicia excelsa*, *Terminalia superba*, *Terminalia ivorensis*, *Persea americana*, and *Morinda lucida*) in cocoa agroforestry systems in dry and moist semi-deciduous ecological zones of Ghana at Offinso Municipality and Adansi-Asokwa District respectively. Data was collected from five shade trees species from six different farms in each ecological zone. The results revealed that *Morinda lucida* and *Persea americana* were evergreen in both ecological zones, *Terminalia ivorensis* developed leaves from March but in May in the Moist and Dry semi-deciduous ecological zones respectively. *Milicia excelsa* was inconsistent in flower and fruit formation among the ecological zones in January and February but *Terminalia superba* flowered and fruited in both ecological zones between March and May. Litterfall was generally higher in the Moist semi-deciduous ecological zone with *Persea americana* and *Morinda lucida* recorded highest of 47.00t/ha/yr and 45.08t/ha/y respectively while *Milicia excelsa* recorded least (24.97t/ha/yr). Rainfall and relative humidity had a strong and significant negative relationship with litterfall ($r = -0.645$, $P = 0.02$) and ($r = -0.633$, $P = 0.001$) respectively. Temperature had weak positive relationship with litterfall ($r = 0.138$). Increase in rainfall and humidity reduced litterfall but a reverse was observed in both ecological zones. Farmers' knowledge on litterfall is important as it greatly influence carbon sequestration, nutrient cycling, and soil fertility in cocoa agroforestry systems.

Keywords: Climate change; Litterfall; Climatic parameters; Cocoa shade trees, Cocoa agroforestry systems

Introduction

Cocoa is an important part of Ghana's agricultural sector, contributing significantly to the nation's economy and providing livelihoods for millions of rural households (Teye et al. 2024). Cocoa is not only a significant income source for smallholder farmers, but also enhances food security for households (Hashmiu et al. 2022). Ghana's cocoa sector alone creates about 800,000 jobs across the country (Maguire-Rajpaul et al. 2020; Afele et al. 2021). Nowadays, cocoa farmers are challenged with increased temperature, unreliable rainfall pattern and prolong dry season which negatively affect cocoa production (Ariza-Salamanca et al. 2023; Kohl et al. 2024). To reduce the effects of changing climatic conditions on cocoa trees, farmers plant shade trees in their cocoa farms as an adaptation strategy to increase cocoa yield (Kohl et al., 2024) as shade trees protect high heat index in cocoa farms (Mensah 2023). Ríos-Bolívar et al. (2022) further explained from their research that high farm temperatures above 40 °C significantly impair physiological activities in cocoa trees, especially photosynthesis and water transport to the various parts of the plant which could affect cocoa yield.

Litterfall, which is an important component of forest nutrient cycling and carbon input is strongly influenced by changes in climatic conditions such as temperature, rainfall, and humidity as it affects timing, quantity of litterfall, litter decomposition rate as well as soil fertility (Giweta 2020). Other studies including Saj et al. (2021) and Zhao et al. (2022) further showed that changes in temperature and rainfall patterns greatly influence litterfall and soil fertility in cocoa agroforestry systems. There is an increasing awareness of the impact of climate change on cocoa production and farmers' adaptation strategy of integrating shade trees in cocoa farms to combat its effect. However, little research has focused on effects of changes in climatic factors on phenology (leafing, flowering, fruiting, and litterfall) of shade trees in cocoa agroforestry systems. This study

therefore investigated the effects of change in climatic factors on phenology of five selected shade trees, *Milicia excelsa*, *Terminalia superba*, *Terminalia ivorensis*, *Persea americana* and *Morinda leucida* in cocoa agroforestry systems in the dry and moist semi-deciduous ecological zones in Ashanti region of Ghana.

Materials and Methods

Study area description

The study was conducted in dry Semi-deciduous and Moist semi-deciduous zones at Offinso Municipality and Adansi Asokwa District of Ghana respectively. The Offinso Municipal District is found in the North-western part of the Ashanti Region of Ghana and lies between latitudes 6°95'N and 7°15'N, and longitudes 1°35'W and 1°50'W (Fig. 1) with total population of about 137,272 of which About 58.6% fall between ages 15 and 64 years (Ghana Statistical Service 2021). The Adansi Asokwa District is in the southern part of Ashanti Region, Ghana with a total population of 71,844 of which 56.6% fall between ages 15 and 64 years (Ghana Statistical Service 2021). The district lies between latitudes 1.4N and 6.30N, and longitudes 1.50W and 1.5W. There are two rainy season patterns in the both districts thus April-July and September-November with average annual rainfall of 103.83cm and 1500cm in Offinso Municipality and Adansi Asokwa District respectively. The driest period of both districts is between December and February.

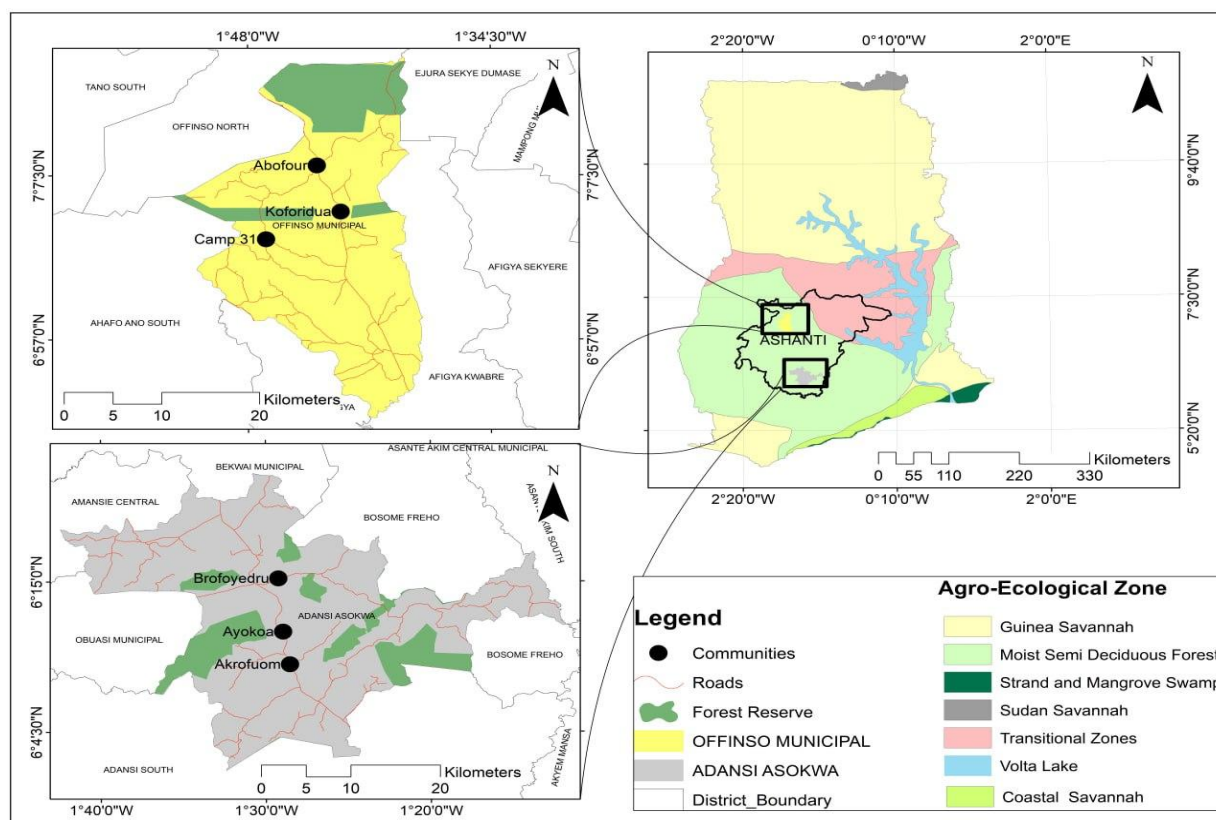


Fig. 1 Map of Ashanti region showing the study areas at Offinso Municipality (Dry semi-deciduous zone) and Adansi Asokwa District (Moist semi-deciduous zone) of Ghana.

Research design and sampling approach

A 100m x 100m plot was demarcated in the cocoa farms for enumeration of the tree species. Cocoa farms with selected shade tree species between 9 and 18 trees per hectare were selected for the study. Geographic positioning system (GPS) coordinates of the farm locations were taken using Garmin Montana 700i. The treatment plots in each ecological zone were hybrid medium and amazon medium shading systems with three (3) replications, thus making six (6) plots. Therefore, a total number of twelve (12) plots were used in the two ecological zones. Two (2) automatic Campbell Scientific Meteorological Stations were installed in each ecozone to monitor air temperature, relative humidity, rainfall, solar radiation above and below the cocoa canopy areas in

176 hybrid-medium shade and amazon-medium shade areas. Each of the four (4) stations was
177 connected to Campbell scientific CR300 data logger, silicon pyranometer solar radiation sensor,
178 temperature sensor, relative humidity sensor, and rain gauge tipping bucket to monitor weather
179 events. Each of the monitoring equipment was positioned above and below the cocoa canopy areas
180 of dry and moist semi-deciduous zones to monitor weather changes in the plots.

181 Litter traps were made of 0.50 m x 0.50 m PVC tubes framed with open catching collectors of
182 1mm nylon screen mesh base. The traps were attached to a frame of durable material, with a known
183 catching area of 0.25 m². The litter bags (collecting funnels) were at least 0.5 m deep to prevent
184 litter from being blown out (Pitman et al. 2010). The traps were mounted on four PVC tube stands
185 100 cm (1 m) above the ground level to ensure clearance from the ground and for efficient
186 capturing of litter. Each shade tree had one litter trap mounted under it, carefully placed in open
187 areas where the cocoa canopies could not interfere with the litterfall. Five litter traps were installed
188 in each plot, therefore thirty (30) traps per each ecological zone were mounted, giving a total of
189 sixty (60) litter traps in both moist and dry semi-deciduous zones.

190 The litter traps were carefully distributed within the experimental plots to ensure
191 representativeness and their positions were changed every eight weeks (Santhyami 2022). Litter
192 was collected at four (4) weeks intervals using labelled zip lock collection bags to avoid pre-
193 collection decomposition in the traps. Litter collected were manually separated into fractions;
194 leaves, twigs and branches and floral parts (flowers and seeds). The monthly values of collected
195 litter were summed up for the annual litterfall in the two ecological zones. Collection bags were
196 labelled with shade type, tree name, tree number, ecozone and date of collection. Data entries were
197 made on record sheets.

198

Results

Leafing pattern of shade trees in the dry and moist semi-deciduous ecological zones

Results showed that *Morinda lucida* and *Persea americana* were evergreen in both ecological zones. Delay in leafing of *Terminalia ivorensis* both ecological zones was observed, with the dry ecological zone developing leaves in May, and moist ecological zones having leaves in March (Fig. 2).

Species	Ecological Zone	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
<i>M. excelsa</i>	Dry												
	Moist												
<i>T. superba</i>	Dry												
	Moist												
<i>T. ivorensis</i>	Dry												
	Moist												
<i>P. americana</i>	Dry												
	Moist												
<i>M. lucida</i>	Dry												
	Moist												

Fig. 2 Leafing pattern of shade trees in both dry and moist semi-deciduous ecological zones of Ghana

Flowering pattern of the shade trees in the dry and moist semi-deciduous ecological zones

Milicia excelsa did not flower throughout the year in the dry semi-deciduous zone but had flowers in January and February in the moist semi-deciduous. Flowers were recorded in July and August for *Terminalia ivorensis* in the dry semi-deciduous zone but in the moist semi-deciduous zone, flowers were recorded in May and June. *Persea americana* recorded flowers in October in both ecological zones, and *Morinda lucida* also recorded flowers in January in both ecological zones (Fig. 3).

Species	Ecological Zone	Jan.	Feb.	Mar.	Apr.	May	Jun	Jul.	Aug	Sep.	Oct.	Nov.	Dec.
<i>M. excelsa</i>	Dry												
	Moist												
<i>T. superba</i>	Dry												
	Moist												
<i>T. ivorensis</i>	Dry												
	Moist												
<i>P. americana</i>	Dry												
	Moist												
<i>M. lucida</i>	Dry												
	Moist												

Fig. 3 Flowering pattern of shade trees in both dry and moist semi-deciduous ecological zones

Fruiting pattern of the shade trees in the dry and moist semi-deciduous ecological zones

Milicia excelsa in the dry semi-deciduous did not fruit but recorded fruits in May and June in the moist semi-deciduous zone. *Terminalia ivorensis* had fruits in October in the dry semi-deciduous, but in August and September in the moist semi-deciduous. *Persea americana* had fruits from January through to March in both ecological zones, and *Morinda lucida* had fruits from April to June in both ecological zones (Fig. 4).

Species	Ecological Zone	Jan.	Feb.	Mar.	Apr.	May.	Jun	Jul	Aug.	Sep.	Oct.	Nov.	Dec.
<i>M. excelsa</i>	Dry												
	Moist												
<i>T. superba</i>	Dry												
	Moist												
<i>T. ivorensis</i>	Dry												
	Moist												
<i>P. americana</i>	Dry												
	Moist												
<i>M. lucida</i>	Dry												
	Moist												

Fig. 4 Flowering pattern of shade trees in both dry and moist semi-deciduous ecological zones

Mean total annual litterfall for all five species in tons per hectare per year in the dry and moist semi-deciduous ecological zones

Generally, litterfall in the moist semi-deciduous zones was relatively higher than in the dry semi-deciduous zones. *Milicia excelsa* had the least litterfall in the dry semi-deciduous zone

(24.97t/ha/yr), and *Persea americana* had the highest litterfall in the moist semi-deciduous zone, (47.00t/ha/yr). The other species ranged between the least and the highest in both dry and moist semi-deciduous zones (Table 1).

Table 1 Mean total annual litterfall in Dry and Moist semi-deciduous ecological zones

Ecological zones	Annual litterfall (t/ha/yr)				
	<i>M. excelsa</i>	<i>T. superba</i>	<i>T. ivorensis</i>	<i>P. americana</i>	<i>M. lucida</i>
Dry semi-deciduous zone	24.97±11.93 ^a	32.60±14.07 ^b	33.59±9.83 ^c	44.51±8.04 ^e	43.61±12.22 ^d
Moist semi-deciduous zone	25.03±12.06 ^a	33.75±11.74 ^b	34.99±9.39 ^c	47.00±12.45 ^e	45.08±12.52 ^d

*Means are compared horizontally between the species, from left to right

Seasonality of temperature, rainfall and litterfall in the dry semi deciduous ecological zones

Generally, high temperature and low rainfall periods in the major dry season (Nov-Jan) resulted in increased litterfall in dry ecological zones A similar trend was observed during minor dry season (Feb-Apr) and minor rain season (Aug-Oct) where temperatures were higher, and rainfall was relatively lower (Fig. 5 and 6).

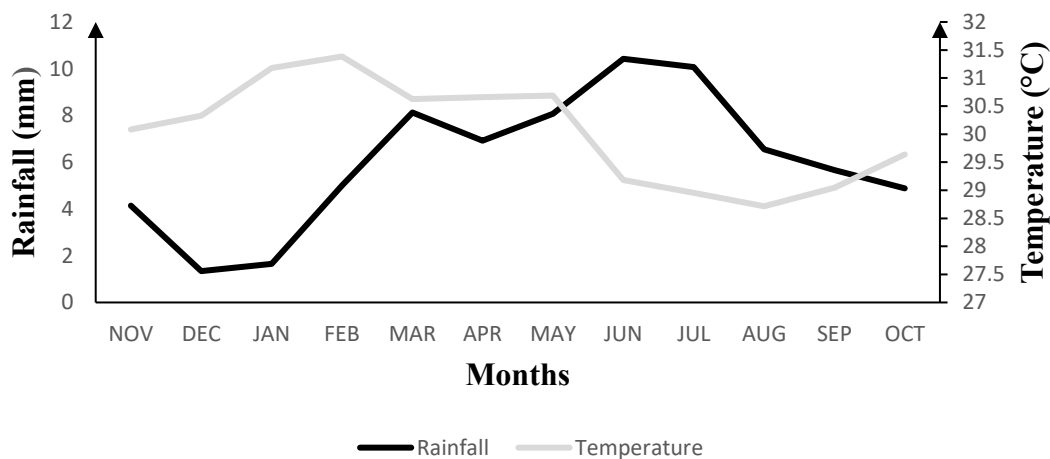


Fig. 5 Temperature and rainfall patterns across the year in Dry semi deciduous ecological zone of Ghana

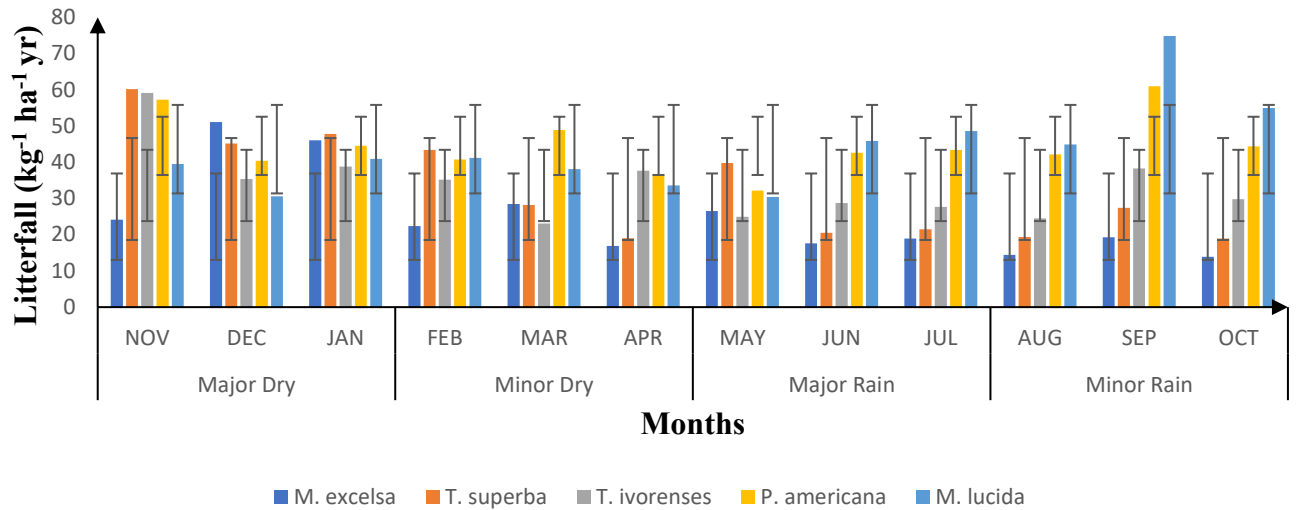


Fig. 6 Seasonality of temperature, rainfall and litterfall in the Dry semi deciduous ecological zone of Ghana

Seasonality of temperature, rainfall and litterfall in the moist semi deciduous ecological zones of Ghana.

Generally, high temperatures and low rainfall periods increased litterfall values in the moist ecological zones. During the major dry season (Nov-Jan), temperatures were high, rainfall was low but litterfall increased. In the minor rain season (Aug-Oct), temperatures were low, rainfall was lower and litterfall was low. In the major rain season, rainfall was higher, temperatures were lower, and litterfall was relatively lower in the moist semi deciduous ecological zones of Ghana. (Fig. 7 and 8).

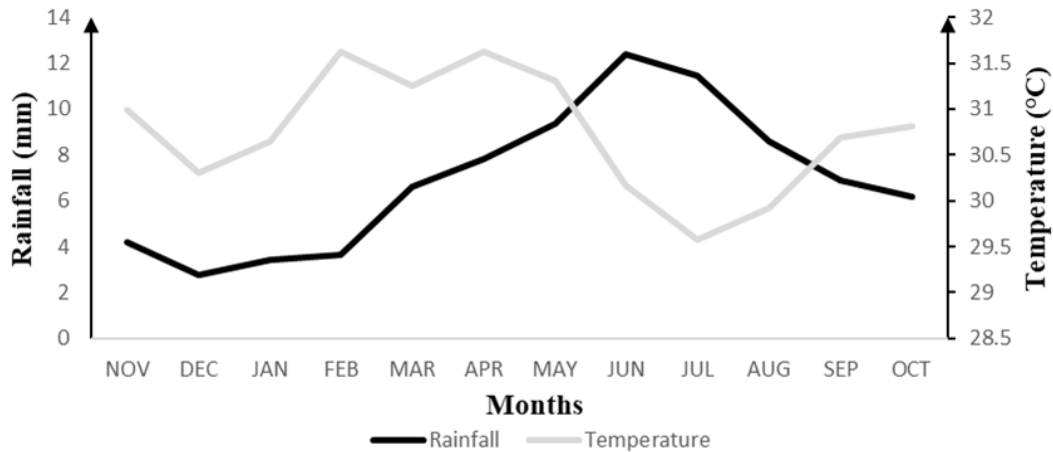


Fig. 7 Temperature and rainfall patterns across the year in the Moist semi deciduous ecological zone of Ghana

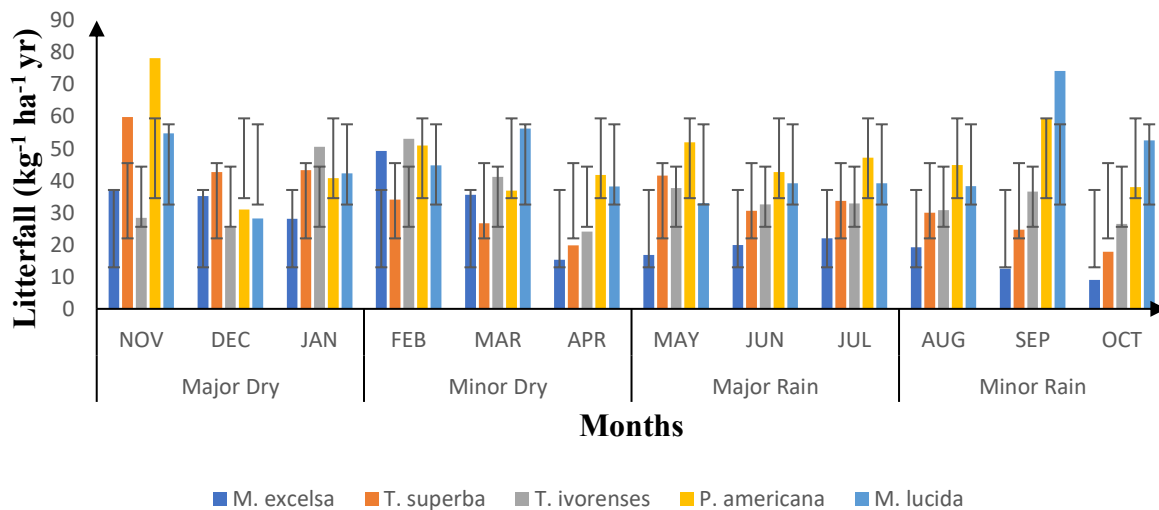


Fig. 8 Seasonality of temperature, rainfall and litterfall in the Moist semi deciduous ecological zone of Ghana

Correlation between litterfall and microclimate parameters in the dry and moist ecological zones of Ghana

Shade tree responses to changes in microclimatic conditions were determined and it was observed that a rise in rainfall resulted in relatively lower amount of litterfall in shade tree species (Fig. 9a).

A strong significant negative relationship was observed between rainfall and litterfall ($r = -0.645$).

There was a strong and significant negative relationship between relative humidity and litterfall ($r = -0.633$), a rise in relative humidity resulted in lower amounts of litterfall in shade tree species (Fig.9b). A rise in temperature resulted in a relatively higher amount of litterfall (Fig. 9c), however, there was a weak positive relationship between temperature and litterfall ($r = 0.138$). Solar radiation had a weak positive relationship with litterfall ($r = 0.091$), however, a rise in solar radiation resulted in higher amounts of litterfall (Fig. 9d).

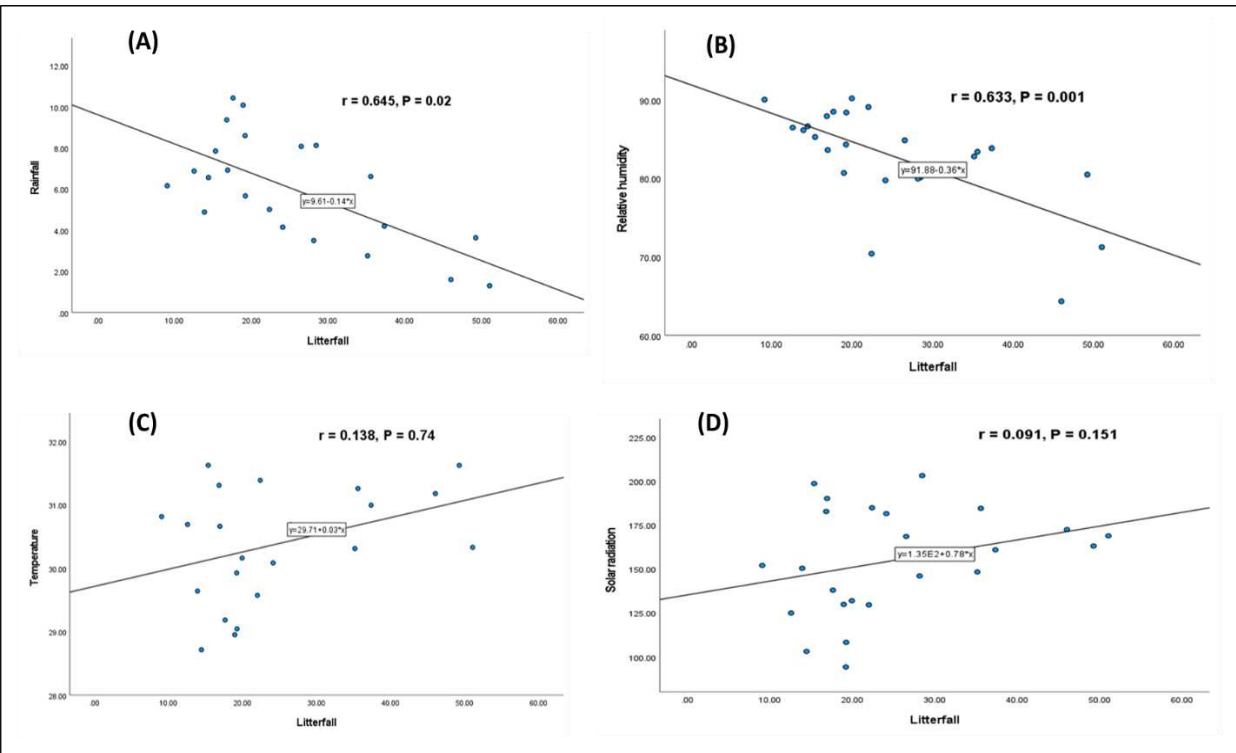


Fig. 9 (a) Correlation between rainfall and litterfall **(b)** Correlation between relative humidity and litterfall **(c)** Correlation between temperature and litterfall **(d)** Correlation between solar radiation and litterfall of Offinso Municipality (Dry semi-deciduous) and Adansi Asokwa District (Moist semi-deciduous) of Ghana

Discussions

Leafing, flowering, and fruiting pattern of the shade trees in the dry and moist semi-deciduous ecological zone

Leafing patterns for the five shade trees in the dry and moist ecological semi-deciduous ecological zones show significant similarities except *Terminalia ivorensis* that showed delay in leafing in the two ecological zones in response to changes in climatic conditions including temperature and rainfall which play a vital role in leaf development. This study is in line with findings of research by Dwivedi and Chandla (2024) which stated that phenological pattern of tropical forest tree species adapts their leafing periods to optimize functions and reduce environmental stress because of climate change.

Flowering and fruiting patterns of shade trees in the dry and moist semi-deciduous ecological zones were consistent, except for *Milicia excelsa* which did not flower and fruit in the dry semi-deciduous zone but flowered in the moist semi-deciduous ecological zone (Table 2). Changes in environmental factors that affect soil productivity including rainfall and temperature in the dry semi-deciduous zone could have influenced flowering and fruiting of *Milicia excelsa* as reported by Nigatu (2024). Similarly, studies by Rebolledo et al. (2025) indicates that flowering and fruiting patterns of tropical trees are highly influenced by water availability, soil characteristics, and temperature change. Shade trees that adapt to their local microclimate and changing environmental conditions flower and fruit in each year across the ecological zones (Yadav 2024).

Litterfall and microclimate changes of shade trees in the dry and moist semi-deciduous ecological zone

Litterfall in the dry semi-deciduous zone was strongly influenced by seasonal changes including temperature and rainfall. During the major dry season (Nov-Jan), increase in temperature significantly increased litterfall. This phenomenon is more pronounced in tree species with large canopy coverage and higher rates of leaf shedding (Morffi-Mestre et al. 2020). The increase in litterfall in dry season in response to increased water stress helped reduce transpiration (Brodrribb

et al. 2020). Studies on dry semi-deciduous forests in Ghana have similarly shown that elevated temperatures, combined with low soil moisture, triggered litterfall (Ibrahim et al. 2025). During the wet season (May to October), a clear correlation existed between rainfall and litterfall, suggesting that moisture availability accelerated leaf production and subsequent shedding from the study. The gradual rise in litterfall from the major rain season to the minor rain season aligns with findings of Giweta (2020) and Zhou (2025) that water availability during rainy season promotes vegetative growth, leading to more litter production. The peak in litterfall in *Persea americana* and *Morinda lucida* in September suggests that excess moisture and strong wind in the major rainy season triggered leaf abscission (Obando et al. 2023). Tonin et al. (2021) similarly reported that larger canopy trees contribute to litterfall, especially during the dry season to reduce transpiration and water stress.

However, in the moist semi-deciduous ecological zone, litterfall patterns exhibited a more balanced response to both temperature and rainfall changes throughout the year compared to dry semi-deciduous zone, where sharp increase in litterfall was recorded in dry season. Koala and Takenaka (2024) noted that in moist forest zones, consistent rainfall reduces water stress leading to a more even distribution of litterfall throughout the year. The moderate peak in litterfall observed in the dry seasons especially in November, coincides with the transition from the minor rain seasons (Sep-Oct) to the dry seasons where a slight increase in temperature induces early shedding. Oyedeji (2023) reported that increase in temperature at the end of the rain season triggers hormonal changes in plants which promote leaf abscission. Rainfall remains a dominant factor during the rainy seasons, with *Morinda lucida* and *Persea americana* responding to abundant moisture by shedding excess leaves during this period. Addo-Fordjour et al. (2024) found similar trends in their study of moist semi-deciduous forests in Ghana, where heavy rains

were associated with increased litter production. According to Asigbaase et al. (2021), some plant species are more sensitive to microclimatic variations, responding to increases in temperature and rainfall. Species-specific differences in the moist zone reflect varying adaptive strategies to microclimatic changes. Species with smaller canopy coverage or drought resilient are less sensitive to temperature and rainfall changes (Köpp Hollunder et al. 2022). These findings highlight the importance of understanding species-specific litterfall patterns in response to microclimatic changes, as these dynamics have significant implications for nutrient cycling and forest ecosystem productivity (una-Nieves et al. 2022; Chaturvedi et al. 2025).

Conclusion

Leafing patterns of *Morinda lucida* and *Persea americana* were evergreen, *Terminalia ivorensis* recorded leaves from March in the moist semi-deciduous ecological zone, but May in the dry semi-deciduous ecological zone. *Milicia excelsa* did not flower in the dry semi-deciduous ecological zone but flowered from January to February in the moist semi-deciduous zone. *Terminalia superba* flowered between March and May in both ecological zones. *Milicia excelsa* fruited between May and June in the moist semi-deciduous ecological zone, *Terminalia superba* recorded fruits in July and August in the moist semi-deciduous ecological zone. Litterfall was high in the moist semi-deciduous zone than the dry semi-deciduous zone, with the highest recording for *Persea americana* and the least for *Terminalia superba* respectively. Increase in rainfall and relative humidity reduced litterfall but a rise in temperature increased litterfall in both ecological zones.

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438 **Competing Interest**

439 The authors declare no competing interest.

440 **Authors contributions**

441 Victor Rex Barnes, Isaac Bowah Cudjoe, Daniel Dompok, Kwame Twum-Ampofo, Uffe Jørgensen, Steve
442 Amissah, Olivia Agbeyenga, Finn Plauborg, Torsten Rodel Berg, Soren Marcus Pedersen, Maxwell Osei Hene and
443 Judith Osei Nimo jointly conceived the research idea. Material preparation, data collection and
444 analysis were performed by Victor Rex Barnes, Isaac Bowah Cudjoe, Daniel Dompok, Kwame Twum-
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449 reviewed and edited the manuscript. All authors read and approved the final version of the
450 manuscript.

451 **Data availability**

452 The datasets generated during and/or analysed during the current study are available from the
453 corresponding author on reasonable request.

454 **Plant guidelines**

455 The collection of the plants/plant parts (*Milicia excelsa*, *Terminalia superba*, *Terminalia*
456 *ivorensis*, *Persea americana*, and *Morinda lucida*) used in this study complied with local
457 guidelines. Permissions were given by farmers in communities whose farms were used for data
458 collection of the study.

459 **Ethical Approval (Human Studies)**

460 The authors confirm that no human part was used in the study.

461 **Accordance / Ethical Guidelines Statement**

462 The authors confirm that no human part or human-related procedures were performed in the
463 study.

464 **Consent to publish**

465 Consents to participate and to publish were obtained from all participants. No participant was
466 under 18 years was involved in the study.

467 **Consent to participate**

468 No human subjects were involved in this study.