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Suitable Agroecologies and Sowing Dates for Optimum Vegetative Growth of *Camelina sativa* L. (Cranz)/ Brassicaceae/in Tigray, Ethiopia

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ABSTRACT

Camelina sativa is an oilseed crop cultivated in many parts of the world but not as common in northern Ethiopia. This study investigated its vegetative growth responses across agroecological zones and sowing dates in Tigray. Soil physicochemical properties of the selected six experimental sites (Tabiyas) were analyzed before conducting field experiments. A randomized complete block design was employed. Significant variability in soil characteristics was observed in each experimental site, with pH ranging from 5.1 to 7.2. The highest organic carbon content (9.89%) was found in Tabiya Seret, while the lowest (4.67%) was in Tabiya Emba Rufael. Tabiya Genfel recorded the highest total nitrogen level (1417.1 mg/kg), and Aynalem had the lowest (974.4 mg/kg). Vegetative growth parameters such as plant height, root length, biomass, root–shoot ratio, leaf area, and flowering date were markedly influenced by sowing year, sowing date, and agroecological factors. For instance, Tabiya Genfel exhibited the tallest plants (103.54 cm), whereas the shortest (37.42 cm) were in Tabiya Emba Rufael. Root length varied significantly, with Tabiya Mearey having the longest mean root length (19.152 cm) and Tabiya Seret the shortest (11.608 cm). Dry biomass increased from 4.676 g/plant in 2019–5.975 g/plant in 2020. Higher root–shoot ratios were noted in early-sown plants (0.080) across all agroecological zones. Overall, early sowing dates and highland agroecology, particularly with clay soil textures, enabled the crop to grow better. Further studies on soil fertilization, weeds, and pest control might be required so as to obtain the best growth performance and high yield.

1 | Introduction

Plants are immovable organisms. They are vulnerable to a wide range of abiotic and biotic stresses. Abiotic stresses like humidity, light, nutrient availability, drought, high salinity, extreme temperatures, and freezing conditions can significantly impact the growth and productivity of plants [1]. Climate forecasts point to more frequent heatwaves, altered rainfall patterns, and increased drought severity. These changes are primarily due to a significant increase in greenhouse gases such as carbon dioxide, methane, and nitrous oxide in the atmosphere [2]. Global surface temperature data analysis reveals an increase of 0.6°C over the last century [3], with predictions to rise from 1.4°C to 6.4°C by 2100 [4]. This significant climatic shift poses a major obstacle to agricultural productivity in arid and semi-arid regions. Cultivating adaptable oil crops like *Camelina sativa* plays a crucial role as agricultural commodities in producing high-quality edible oils [5].

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C. sativa has been grown for centuries as an oilseed crop for human consumption. This annual herbaceous plant typically grows between 60 and 120 cm tall at maturity [6], bearing pear-shaped indehiscent siliquas measuring 5–6 mm in diameter. Each siliqua contains 8–15 seeds that exhibit a golden or brown color. It is a rapid-growing plant that can complete its life cycle within 100–120 days [7].

Although there are many claims about the origin of Camelina (*C. sativa*), the precise origin remains uncertain [8]. In recent times, this crop has gotten significant attention worldwide and has become a crucial oilseed crop. Considerable effort is being put into bridging the gap between demand and supply in both bio-based and edible oil markets derived from various oilseed crops such as rapeseed (*Brassica napus* L.), soybean (*Glycine max* L.), and sunflower (*Helianthus annuus* L.) for human consumption and animal feed. Maintaining consistent oil quality would add significant value to emerging oilseed crops like *C. sativa*, which holds a unique fatty acid profile, enabling diverse applications [9].

Food security and healthcare remain critical challenges in developing nations like Ethiopia's Tigray region, where limited access to nutritious foods drives malnutrition and related health issues [10]. Introducing nutritious crops like *C. sativa* into existing farming systems could boost productivity, enhance nutrition, and improve profitability through diversification. Although *C. sativa* shows considerable promise but no studies have evaluated its performance across diverse agroecological zones, sowing dates, and soil conditions in Tigray. Without targeted studies on vegetative growth, phenology, and ecophysiological responses to local soil physicochemical properties, its integration into Ethiopian agriculture remains unproven, hindering efforts to transform regional farming and healthcare systems. This study provided novel insights by evaluating *C. sativa* vegetative growth performance across multiple agroecological zones and sowing dates in Tigray. It is a first field evaluation, a pioneering multi-site (Tigray tabiyas), multiyear (2019–2020) assessment of the crop's vegetative growth responses to agroecological gradients (lowland midland and highland) and sowing dates under semi-arid, rainfed conditions.

2 | Materials and Methods

2.1 | Description of Study Area

The study was conducted from January 2019 to November 2020 in the Tigray regional state of Ethiopia. The Tigray region is located in the north of Ethiopia and is bordered by Eritrea in the north, the Afar region in the east, the Amhara region in the south, and Sudan in the west. The region is located within 12°12'05" - 14°51′ 28″ Northing and 36°30′–40° 30′ Easting. Altitude varies from about 500 m above sea level (masl) in the northeast to almost 4000 masl in the south. According to the agroclimatic classification of Tigray, about 53% of the land is below 1500 masl and is classified as lowland (Qola) with relatively low rainfall and high temperatures, 39% is situated at 1500–2300 masl and is known as medium altitude (Hawsi Degua') with medium rainfall and medium temperatures, and 8% is over 2300 masl and is classified as highland (Degua') with higher rainfall and cooler temperatures [11]. The study was conducted in three woredas (districts) of the Tigray region and six Tabiyas representing different agroecologies (Table 1). They were purposively selected based on their elevation and climatic data (Figure 1).

2.2 | Seed Material Collection

Seeds of *C. sativa* were obtained from the Debrezeyt Agricultural Research Center, which is located at 08° 44' N and 38° 58' E with an altitude of 1900 masl.

2.3 | Experimental Design

The experimental design was a randomized complete block with two sowing dates across all selected tabiyas (lowland, midland, and highland) (Figure 2), with five replications per sowing date. Each plot was 3 m long and 3 m wide and consisted of 10 rows spaced ~30 cm apart. Each plot had a buffer zone of 60 cm between plots, which helped reduce seed movement and prevent the mixing of adjacent plots. The seeding rate was 100 seeds per 3 m of row, and the seeding depth was 2–3 cm. Prior to sowing, the soil physicochemical properties of the plots were analyzed following Ahmed et al. [12].

2.4 | Soil Sampling and Analyses of Soil Physico-Chemical Properties

Samples from each area (0–30 cm deep) were bulked together in a clean, labeled plastic bag using a screw or cheese-corer auger. The chemical and physical soil properties were analyzed at soil laboratories of Mekelle University (Table 2).

2.5 | Morphological Characters Measured

Stem elongation (SL) was measured every 5 days from soil surface level to the highest fully expanded ligule (leaf) using a digital

TABLE 1 | Selected study sites at different agroecologies of three districts.

Agroecology	District	Tabia	Altitude (masl)
Degua (highland)	Degua Tembien (south eastern zone)	Seret	2625.6
		Melfa	2585.5
Hawsi Degua (midland)	Klite Awlaelo (easter zone)	Aynalem	1958
		Genfel	1969
Qola (lowland)	Yechilla Abergelle (central zone)	Mearey	1553
		Emba Rufael	1379.1

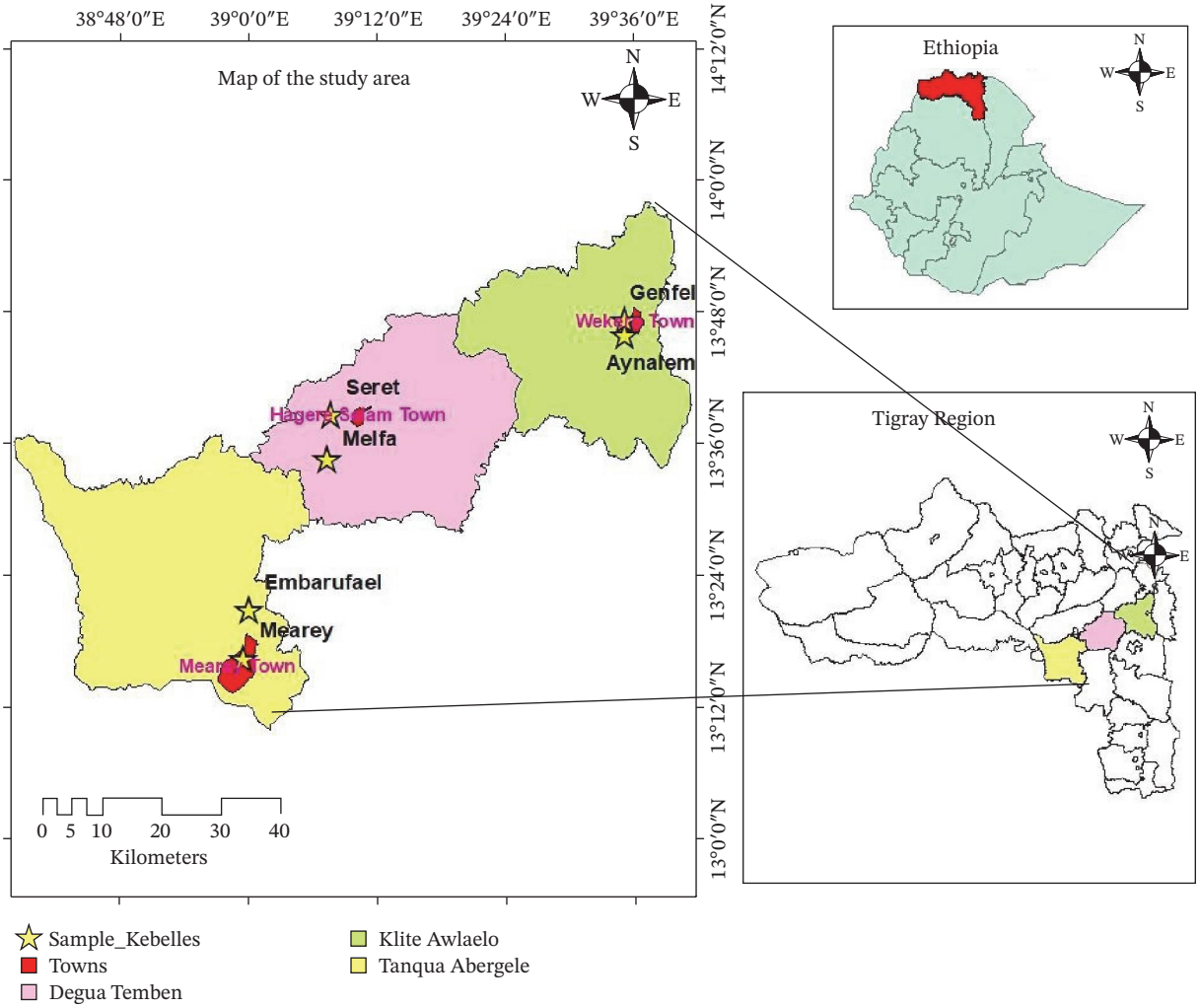


FIGURE 1 | Map of the study area.

TABLE 2 | Analysis of physicochemical properties of soils at the study sites.

Number	Parameter	Method	Reference
1	Soil Textural class	Bouyoucos hydrometer method	[13]
Chemical analysis			
1	Available phosphorus (P_{av})	Extraction	[14]
2	Cation exchange capacity (CEC)	Extraction (using 1M NH_4Ac solution at pH 7)	[15]
3	Organic carbon (OC)	Extraction (Walkely–Black)	[16]
4	Total nitrogen (N tot)	Kjelldahl digestion or Combustion gas analyzer	[17]
5	pH (pH_H_2O & pH_KCl)	Extraction (pH meter)	[18]

caliper (precision: ±1 mm); measurements began in the 2nd week after sowing (seedling stage) and continued at 5-day intervals until harvest, with 20 plants per plot. After maturation, plants were harvested carefully from the soil surface, washed to remove adhering soil, and the following parameters determined immediately in each plot ($n = 20$ plants): shoot length (SL) and root length (RL) using a digital caliper; shoot fresh weight (SFW) and root fresh weight (RFW) using an analytical balance (precision: ±0.01 g). Seedlings were then oven-dried at 65°C for 48 h, after which shoot dry weight (SDW) and root dry weight (RDW) were measured using the same analytical balance (±0.01 g) [19]. Finally, biomass differences, length variations, and overall treatment performance were analyzed.

All data were recorded on a plot-by-plot basis. The days to flowering were determined as the number of days from date of sowing until ~50% of the plants in a plot produced open flowers. During

the flowering time, the flower production of *C. sativa* was estimated as the percentage of branches with flowers in relation to the total number of branches and the percentage of functional flowers or flower heads (number of open flowers or flower heads with visible stamens in relation to the total number of flowers or flower heads) of each sampled plant within treatment. Measurements were conducted twice a week during the most active flowering period. Additionally, the percentage of senescent flowers (number of flowers or bud flower heads with dried petals and stamens in relation to total production) was estimated. Estimations were categorized as 0%, 50%, and 100% [20]. Days to maturity were determined as the number of days from the date of sowing to physiological maturity, i.e., when about 95% of the pod colors were changed and the seeds were stable, representing a moisture content of about 25%. Crop height (cm) was the mean of 10 measurements that were made near to the center of each plot after flowering and prior to color change of maturity.

Growing Degree Days (GDD) is the accumulation of the GDD, which is a cumulative temperature that contributes to plant growth during the growing season. GDD was used to describe the timing of flowering of *C. sativa* and was computed by using the formula described below [21].

$$\mathrm{GDD} = \sum_{i}^{j} \frac{T_{max} + T_{min}}{2} - T_{base},$$

where T_{max}, T_{min}, and T_{base} represent the daily maximum and minimum air temperatures and the base temperature, respectively. A base temperature of 5°C was used for GDD computation. Base temperature (T_{base}) is the minimum temperature at which a crop can be adapted or grown and below that temperature, a crop can't grow in the environment, and that varies with crop type. All temperatures, such as maximum, minimum, and base temperature, were considered during the crop growing period [22]. Weather data, including air temperature and rainfall, were collected at a permanent weather station located near the study woredas (districts) in which the farmer training centers (FTCs) and agricultural research centers of the Tabiayas were found [23].

2.6 | Leaf Area (LA, cm^2)

LA was measured with a portable area meter (Model: E-B95-AM300) [24]. The area of the leaf was measured by fully scanning the fully expanded young leaves.

2.7 | Statistical Analysis

All statistical analyses were performed using SPSS version 20. A three-way analysis of variance (ANOVA) was conducted to evaluate the main effects of agroecology, sowing date, and year, as well as their interactions, on measured parameters. In this mixed-effects model, agroecology, sowing date, and year were treated as fixed factors, with plot (replication) nested within their combinations as the random effect. Post-hoc Tukey's Honestly Significant Difference (HSD) test was applied for mean separation. Treatment and interaction effects were deemed significant at $p \leq 0.05$.

3 | Results and Discussions

3.1 | Physical and Chemical Properties of Soil

In the present study, the textural class of the surface layer (0–30 cm) of the soil profile of the study sites (Tabiyas) Mearey, Emba Rufael, Seret, Melfa, Aynalem, and Genfel were sandy clay, loam, clay, clay, sandy clay loam, and clay loam, respectively. The bulk density of the profile collected from the different Tabiyas of FTCs varied from 1.34 g/cm^3 at Tabiya Aynalem to 1.61 g/cm^3 at the FTC of Tabiya Melfa (Table 3).

3.1.1 | Soil Texture and Particle Size Distribution

Soil texture varied markedly among the sites, reflecting differences in parent material, weathering intensity, and topographic position.

Mearey had a relatively high clay content combined with substantial sand and very low silt. The sandy clay texture suggests moderate water-holding capacity but potentially reduced infiltration compared to lighter soils. The low silt fraction may limit aggregate stability.

Emba Rufael exhibited a balanced particle-size distribution. Loam soils are generally favorable for crop production due to good water retention, aeration, and workability. The relatively lower clay content (18%) indicates moderate nutrient retention compared to clay-dominant sites.

Seret had high clay and silt contents with low sand. Clay soils typically have high water-holding capacity and nutrient retention but may suffer from poor drainage and aeration. The high

TABLE 3 | Soil physical features (0–30 cm of depth) at the beginning of the experiment in the two test years (2019 and 2020).

	Experimental sites (Tabiyas)					
Variables	**Mearey**	**Emba Rufael**	**Seret**	**Melfa**	**Aynalem**	**Genfel**
Sand (%)	47	49	19	25	67	29
Silt (%)	11	33	39	31	11	41
Clay (%)	42	18	42	44	22	30
Bulk density (g/cm^3)	1.39	1.38	1.56	1.61	1.34	1.42
Textural Class USDA	Sandy clay	Loam	Clay	Clay	Sandy clay loam	Clay loam
Altitude (m.a.s.l.)	1553	1379.1	2625.6	2586.5	1958	1969

TABLE 4 | Mean values of soil chemical features (0–30 cm of depth) at the beginning of the experiment in the two test years.

	Experimental sites (Tabiyas)											
	Mearey		Emba Rufael		Seret		Melfa		Aynalem		Genfel	
Variables	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020	2019	2020
OC (%)	7.21	7.64	4.67	4.74	9.89	9.78	9.55	9.48	6.67	6.81	9.35	9.58
TN (mg/kg)	1303.	1310.	1294.0	1289.	1346.9	1348.1	1303.2	1308.1	974.4	977.1	1415.9	1417.1
Ava. P (mg/kg)	168.8	171.4	169.7	170.5	192.8	194.3	192.8	193.2	137.5	138.6	202.6	203.2
Ava. S (mg/kg)	38.1	39.7	37.2	36.8	42.5	44.2	36.9	37.0	29.6	30.1	31.6	32.2
Zn (mg/kg)	1.95	1.98	1.8	1.9	2.3	2.4	2.6	2.8	0.5	0.9	2.2	2.5
Fe (mg/kg)	286.4	289.1	303.9	300.1	332.4	333.1	341.2	343.4	69.9	70.4	325.5	327.4
B (mg/kg)	0.02	0.03	0.02	0.02	0.04	0.04	0.04	0.05	0.01	0.02	0.04	0.05
CEC (cmol(+)/kg)	4.7	4.8	4.6	4.8	5.8	5.7	5.9	5.8	2.4	2.5	4.2	4.5
PH	7.1	5.8	5.5	5.7	6.8	6.8	6.1	6.4	5.1	5.8	6.2	6.3
Exch.Na (mg/kg)	65.8	66.2	80.8	79.3	146.2	147.9	130.3	131.1	67.3	68.6	126.4	125.9
Exch.K (mg/kg)	51.2	52.4	48.4	49.6	64.4	63.8	63.1	65.1	58.1	57.9	58.1	59.6
Exch.Ca (mg/kg)	49.3	50.7	13	12.8	142	145	135.4	136.2	41	42.0	74.3	74.1
Exch.Mg (mg/kg)	131.4	134.5	137	138	144	146	131.4	132.6	104	103.0	122	124.1

Abbreviations: Ava. P, available phosphorus; Ava. S, available sulfur; B, boron; CEC, cation exchange capacity; cmol(+)/kg, centimole charges per kilogram; Exch. Ca, exchangeable calcium; Exch. K, exchangeable potassium; Exch. Mg, exchangeable magnesium; Exch. Na, exchangeable sodium; Fe, iron; OC (%), percent organic content; pH, potential of hydrogen; TN, total nitrogen; Zn, zinc.

altitude may also influence slower organic matter decomposition and soil development.

Melfa had the highest clay content (44%) among the sites. Such soils tend to be heavy, with slow permeability and higher compaction risks, which are reflected in their relatively high bulk density.

Aynalem had the highest sand content (67%), indicating coarse texture and likely rapid drainage. Although the clay content (22%) contributes to some moisture retention, the dominance of sand suggests lower water-holding capacity compared to the clay sites.

Genfel exhibited relatively balanced proportions, with moderate clay and high silt content. Clay loam soils typically provide good moisture retention while maintaining better drainage than heavy clays.

3.1.2 | Bulk Density

Bulk density ranged from 1.34 (Aynalem) to 1.61 g/cm^3 (Melfa), indicating variability in soil compaction and porosity. Higher bulk density values in Melfa and Seret correspond with their high clay content, suggesting greater compaction and lower total porosity. Conversely, the lower bulk density at Aynalem aligns with its sandy texture, which promotes higher porosity and better aeration. Generally, bulk density values above 1.55 g/cm^3 in clay soils may restrict root growth and reduce infiltration. Thus, Seret and Melfa may pose greater limitations for root penetration compared to the other sites.

3.1.3 | Influence of Altitude

The sites span a wide altitudinal range (1379–2626 m.a.s.l.). High-altitude sites (Seret and Melfa) were characterized by clay-dominated soils and higher bulk densities, while lower-altitude sites (Mearey and Emba Rufael) showed more sandy and loamy textures. Altitude influences temperature, rainfall patterns, and weathering processes, which in turn affect soil formation and physical properties.

3.1.4 | Comparative Interpretation Across Sites

Overall, these differences (clay-dominated sites: Seret and Melfa; balanced/medium-textured sites: Emba Rufael and Genfel; coarse-textured sites: Aynalem and Mearey) suggest that water retention, drainage, aeration, and susceptibility to compaction varied considerably among the experimental sites at the start of both the 2019 and 2020 growing seasons. Such variability is important for interpreting treatment responses, as soil texture and bulk density strongly influence soil moisture dynamics, nutrient availability, and crop performance. The data on the 0–30 cm soil layer exhibited substantial heterogeneity among the tabiyas. Clay soils (Seret and Melfa) were likely to retain more moisture but experience drainage constraints, while sandy soils (Aynalem) favored drainage but potentially suffered from lower water and nutrient retention. Loam and clay loam soils (Emba Rufael and Genfel) offered comparatively favorable physical conditions for crop growth.

3.2 | Soil Chemical Features (0–30 cm Depth) at the Beginning of the Experiment (2019 and 2020)

Table 4 presents the mean values of selected soil chemical properties at the start of the experiment in 2019 and 2020 across six tabiyas (Mearey, Emba Rufael, Seret, Melfa, Aynalem, and Genfel). Overall, the values show minor variation between the 2

years, indicating relatively stable baseline soil chemical conditions prior to treatment application.

3.2.1 | Organic Carbon (OC %)

OC ranged from 4.67% to 9.89% across sites. The high OC levels in Seret, Melfa, and Genfel may be associated with their clay textures and higher altitudes, which slow organic matter decomposition. Aynalem and Mearey showed moderate OC levels, while Emba Rufael had comparatively lower values. The slight increase in OC from 2019 to 2020 in most sites suggests minimal seasonal fluctuation. Different research in northwest Ethiopia and elsewhere [25–30] showed soils with clay textural classes contain the highest OC content as compared to soils with other textural classes.

3.2.2 | Total Nitrogen (TN, mg/kg)

Total nitrogen followed a similar pattern to OC, ranging from 974.4 to 1417.1 mg/kg. The highest TN was at Genfel (≈1416–1417 mg/kg), while the lowest was at Aynalem (≈974–977 mg/kg). The strong correspondence between OC and TN indicates that soil nitrogen is largely associated with organic matter content. Clay-rich sites (Seret and Melfa) also maintained relatively high TN levels.

3.2.3 | Available Phosphorus (Ava. P, mg/kg)

Available phosphorus ranged from 137.5 to 203.2 mg/kg. The highest was at Genfel (202.6–203.2 mg/kg) and the lowest at Aynalem (137.5–138.6 mg/kg). Seret and Melfa also recorded high *p* values (~193–194 mg/kg). The relatively high phosphorus levels across sites indicate good P availability at the beginning of the experiment. Year-to-year variation was minimal.

The contents of other important soil nutrients of the study sites are shown in Table 4.

3.2.4 | Cation Exchange Capacity (CEC, cmol(+)/kg)

CEC ranged from 2.4 to 5.9 cmol(+)/kg: highest CEC: Melfa (5.8–5.9), Seret, and lowest at Aynalem (2.4–2.5). Higher CEC values in clay-rich soils (Seret and Melfa) reflect greater nutrient retention capacity. Aynalem's sandy texture corresponds with its low CEC (Table 4).

3.2.5 | Soil Reaction (pH)

Soil pH ranged from **5.1 to 7.1**, indicating slightly acidic to neutral conditions. Neutral to slightly alkaline at Mearey (7.1 in 2019) and moderately acidic at Aynalem (5.1–5.8), Emba Rufael (5.5–5.7)

A noticeable decline in pH occurred in Mearey from 7.1 (2019) to 5.8 (2020), which may require attention. Most other sites showed slight pH increases in 2020.

3.2.6 | Exchangeable Bases

Although Na levels varied, no extreme sodicity risk was evident. The range was 65.8–147.9 mg/kg: highest at Seret and lowest at Mearey. The exchangeable potassium ranged from *r* 48.4 to 65.1 mg/kg: highest at Seret and Melfa but relatively uniform across sites. Exchangeable Ca and Mg were substantially higher in clay-rich sites, consistent with higher CEC values. The exchangeable calcium ranged from 12.8 to 145 mg/kg (highest at Seret and Melfa, lowest at Emba Rufael), while that of Mg was 103–146 mg/kg (highest at Seret and lowest at Aynalem).

3.2.7 | Year-to-Year Comparison (2019 vs. 2020)

Across all sites, differences between 2019 and 2020 were minimal. Most parameters showed slight increases in 2020. The overall soil fertility status remained relatively stable at the beginning of both test years.

3.2.8 | Overall Comparative Assessment of Sites

Clay-dominated sites (Seret and Melfa) exhibited higher OC, TN, CEC, and exchangeable bases, reflecting stronger nutrient-holding capacity. In contrast, the sandy-dominant Aynalem showed lower OC, TN, micronutrients, and CEC, indicating comparatively lower inherent fertility. In general, at the start of the experiment in both 2019 and 2020, the soils across the six tabiyas displayed considerable spatial variability in chemical properties but minimal interannual variation. Clay-rich sites (Seret and Melfa) had superior nutrient retention and higher fertility indicators, while sandy soils (Aynalem) showed lower nutrient reserves and CEC.

3.3 | Vegetative Growth

3.3.1 | Plant Height (cm)

Plant height (measured by digital caliper) was pointedly greater in the plants sown in June than the camelina plants sown in July (Table 5). It was significantly affected by sowing date, site (nutrient content), and by their interaction (Table 6). The highest average plant height (92.514 cm) was recorded in *C. sativa* plants grown in Wereda Kilte Awlae'lo, Tabiya Genfel, and the lowest average plant height (37.432 cm) was observed in Yechila Abergele district, Tabiya Emba Rufael (Figure 3). *C. sativa* seeds sown in the second growing year (2020) of the cultivation season showed better shoot height compared to those sown in the first year (2019) of the farming season in all sites (Tabiyas) and sowing dates (Figure 3 and Table 7). It was corresponding to the amount of rainfall in the two sowing years (higher in 2020). The present results agreed with a previous study conducted by Etana et al. [31] on the effect of growing year on cowpea (*Vigna unguiculata*) in the central rift valley of Ethiopia. With the increase of agro-ecological elevation, the tallest plants were recorded at the highest altitude of 1969–2625.6 m.a.s.l. (Table 1, Figure 3). Similar to the present study, Sido et al. [32] in southern Ethiopia reported comparable findings, with a significant difference in camelina plant height cultivated in lowland (Qola) (1500 m.a.s.l.), midland (Hawsi Degua) (1958 m.a.s.l.), and highland (Degua) (2500 m.a.s.l.) areas.

Similar positive correlations between plant height and agroecological elevation were reported on other cereals, including wheat (*Triticum aestivum* L.) [33], rice (*Oryza sativa* L.), and millet (*Panicum miliaceum* L.) [34]. This could probably be explained

TABLE 5 | Means comparison of the traits under different sowing date of *C. sativa*.

Sowing Date	SL (cm)	RL (cm)	SFW (gm)	RFW (gm)	SDW (gm)	RDW (gm)	LA (cm^2)	RSR
FWJN	62.868	16.448	18.577	5.975	6.799	0.509	16.047	0.080
FWJLY	54.420	12.723	11.897	3.728	3.852	0.252	17.450	0.077
Error	0.007	0.004	0.004	0.009	0.002	0.000	0.112	0.000
Sign. ($p \leq 0.05$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Abbreviations: FWJLY, first week of July; FWJN, first week of June; LA, leaf area; RDW, root dry weight; RFW, root fresh weight; RL, root length; RSR, root–shoot ratio; SDW, shoot dry weight; SFW, shoot fresh weight; SL, shoot length.

TABLE 6 | Analysis of variance for vegetation growth of *Camelina sativa* grown under different study sites (Tabiyas), sowing dates, and sowing years.

Source	SL (cm)	RL (cm)	SFW (gm)	RFW (gm)	SDW (gm)	RDW gm)	LA (cm^2)	RSR
Site (Tabiya)	104206.761*	3145.460*	14797.158*	3109.555*	2114.118*	14.166*	19454.08	0.099*
Sowing Year	17310.175*	16909.39*	17893.779*	576.555*	1011.457*	0.652*	42377.73	0.263*
Sowing date	42805.241*	8323.146*	26758.726*	3026.768*	5208.601*	39.758*	1180.870	0.006
Site (Tabiya)* sowing year	570.647*	20.997	88.356*	10.537	3.683	0.060	15964.100	0.011*
Site (Tabiya)* sowing date	1036.863*	285.916*	600.165*	180.239	126.516*	2.662*	13856.524	0.073*
Sowing year* sowing date	85.365	5.460	88.353*	0.526	4.654	0.047	15894.058	0.042*
Site (Tabiya)* sowing year* sowing date	567.933*	20.402	87.277	10.536	3.704	0.060	15964.100	0.007*
Std. error	59.567	21.117	19.096	113.035	3.021	0.095	15990.794	0.003

Abbreviations: LA, leaf area; RDW, root dry weight; RFW, root fresh weight; RL, root length; RSR, root–shoot ratio; SDW, shoot dry weight; SFW, shoot fresh weight; SL, shoot length.
*Significant at $p \leq 0.05$.

by the responses of camelina to the various growing conditions, including the chemical and physical properties of the soil, precipitation, and mean temperature in each site. Such factors could change the plant growth and increase the number and length of internodes as the contributors to progressive increase in plant height [35–37]. Multiple locations provided different conditions for camelina seedling growth. These results suggest that camelina seedlings are capable of surviving in a variety of climatic and edaphic conditions [37].

The vegetative growth of *C. sativa* sown in June was higher than that of those sown later in July (Table 5). The average plant height of the June-sown camelina was 55.958 cm (2019) and 61.330 cm (2020) at the three agroecological zones of Tigray, including the districts of Yechila Abergele (lowland) (Tabiyas Emba Rufael and Mearey), Kilte Awlae'lo (midland) (Tabiyas Aynalem and Genfel), and Dogua'Temben (highland) (Tabiyas Seret and Melfa (Figure 3). This might have been due to camelina's vigorous early-season growth, completing its vegetative cycle before the end of the rainy months [38]. Environmental conditions, including moisture, light, and temperature are favorable for the growth of camelina when sown in early spring [39].

3.3.2 | RL (cm)

The analysis of variance (ANOVA) conducted on the RL of *C. sativa* plants across different study sites (Tabiyas), sowing years, and sowing dates, and their interactions showed that growth was significantly affected (Table 6). This implies that these factors are crucial in determining the root growth of camelina under open rainfed conditions. The comparison means (HSD) at a 5% significance level revealed significant differences in RL across different study sites (Tabiyas) (Table 8). Specifically, Tabiya Mearey recorded the highest mean RL of 19.152 cm, whereas Tabiya Seret recorded the lowest mean RL of 11.61 cm. This indicates that the agroecological environment plays a significant role in influencing root development in camelina plants. The study also highlighted the influence of sowing year and sowing date on RL. Plants sown in early June 2020 exhibited significantly longer roots compared to those sown in July 2019 (Figure 4). Different researchers found similar findings in different agroecologies [36]. The timing of sowing can affect root growth, possibly due to variations in moisture level, temperature, and other environmental conditions or plant developmental stages at different times [40]. In the lowland, where high temperatures and low moisture prevail, the plant tends to shift its growth more towards the roots to reach very deep water, which reduces shoot growth due to investment differences (more investment in roots compared to shoots by the plant) [41].

3.3.3 | The Root and Shoot Biomass

Based on the three-way interactions of the (study sites [Tabiyas], sowing year, and sowing date) the shoot and root biomass of *C. sativa* were significantly influenced (Table 6). Specifically, agroecological variations of the study sites (Tabiyas: Emba

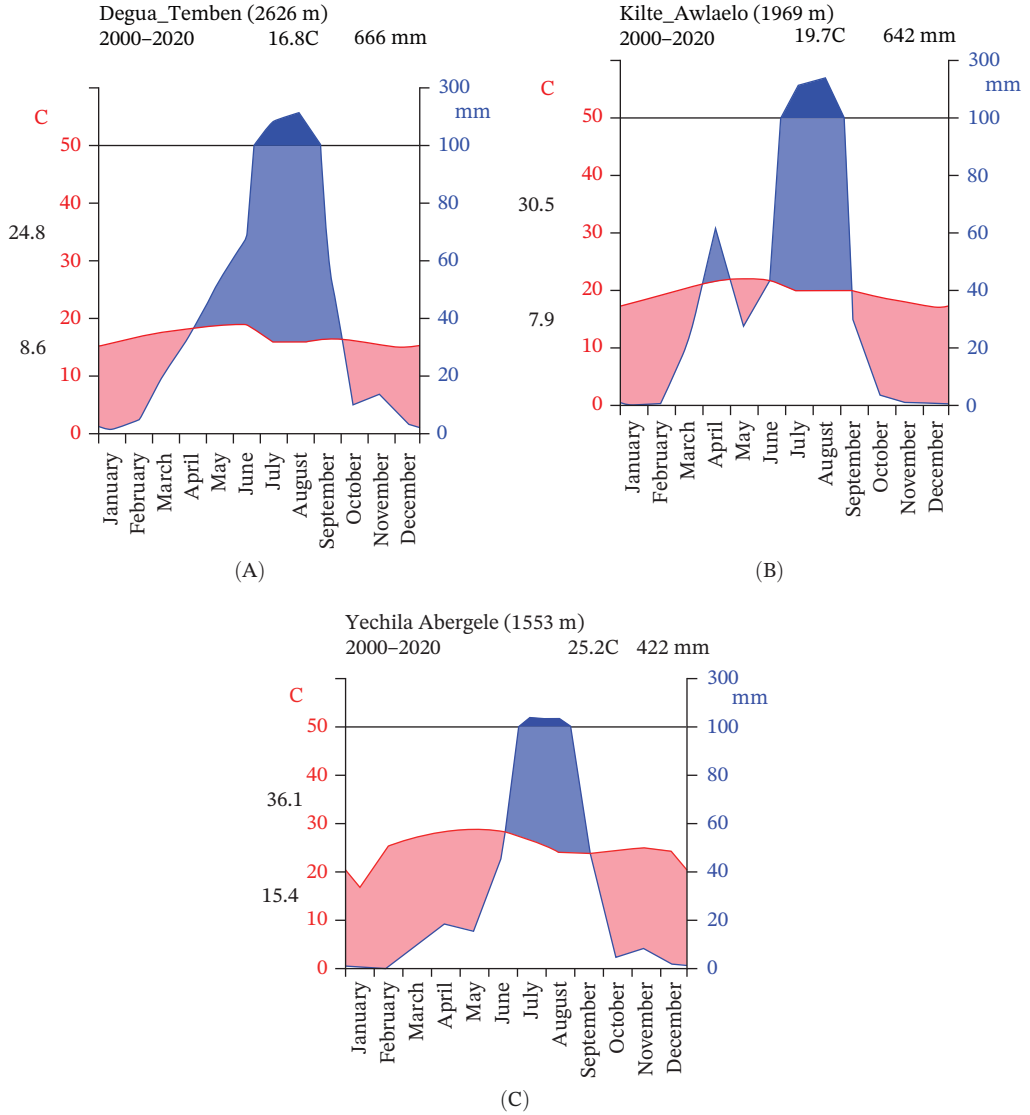


FIGURE 2 | Climate diagram of the study areas. Degua Tembien (A), Kilte Awlaelo (B) and Yechila Abergele (C).

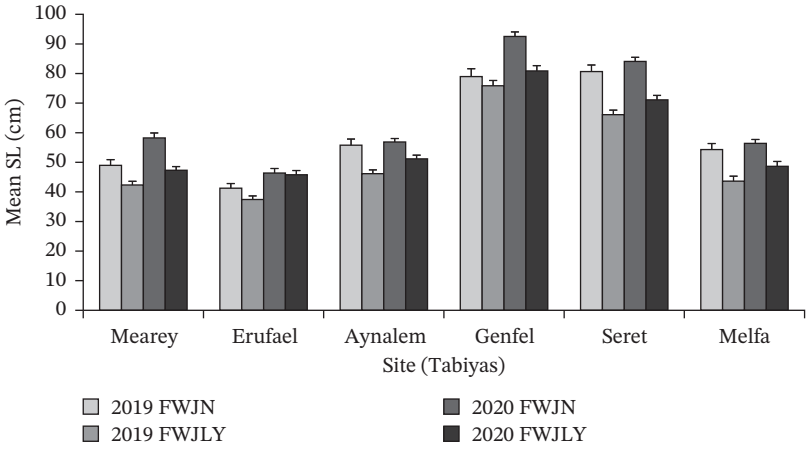


FIGURE 3 | Mean shoot length of *C. sativa* in different sowing dates and study sites (Tabiyas in Tigray).

Rufael, Meary, Aynalem, Genfel, Seret, and Melfa) influenced shoot biomass more than other factors (Table 8). The SFW of *C. sativa* was significantly higher in the Dogua' Temben district (Tabiyas Seret and Melfa) compared to the districts Klite Awlae'lo (Tabiyas Genfel and Aynalem) and Yechila Abergele (Tabiyas Emba Rufael and Mearey). This suggests that higher

TABLE 7 | Means comparison of *C. sativa* grown in different sowing years.

Sowing year	SL (cm)	RL (cm)	SFW (gm)	RFW (gm)	SDW (gm)	RDW (gm)	LA (cm^2)	RSR
2019	55.958	11.930	12.506	4.361	4.676	0.364	12.546	0.089
2020	61.330	17.240	17.968	5.342	5.975	0.397	20.952	0.068
Std. error	0.010	0.006	0.005	0.013	0.002	0.000	0.159	0.000
Significance ($p \leq 0.05$)	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Abbreviations: LA, leaf area; RDW, root dry weight; RFW, root fresh weight; RL, root length; RSR, root–shoot ratio; SDW, shoot dry weight; SFW, shoot fresh weight; SL, shoot length.

TABLE 8 | Means comparison of *C. sativa* grown under different study sites (Tabiyas).

Site (Tabiyas)	SL (cm)	RL (cm)	SFW (gm)	RFW (gm)	SDW (gm)	RDW (gm)	LA (cm^2)	RSR
Mearey	49.21^{a}	19.15^{a}	12.77^{a}	2.42^{a}	3.29^{a}	0.14^{a}	10.85^{a}	0.1^{a}
ERufael	41.86^{b}	12.99^{b}	6.39^{b}	2.11^{b}	2.40^{b}	0.16^{b}	24.51^{b}	0.08^{b}
Aynalem	52.48^{c}	14.15^{c}	12.32^{c}	3.88^{c}	5.75^{c}	0.39^{c}	13.06^{b}	0.08^{c}
Genfel	82.06^{d}	16.65^{d}	17.55^{d}	4.10^{d}	7.09^{d}	0.54^{d}	26.79^{c}	0.08^{d}
Seret	75.49^{e}	11.61^{e}	23.99^{e}	8.12^{e}	8.53^{e}	0.58^{e}	12.66^{d}	0.07^{e}
Melfa	50.74^{f}	12.97^{f}	18.39^{f}	8.49^{f}	4.89^{f}	0.48^{f}	12.63^{b}	0.11^{e}
Std. error	0.01	0.07	0.07	0.02	0.003	0.001	0.195	0.001

Note: Means with the same letters in each column are not significantly different at 0.05 according to Post Hoc Tukey's HSD test.
Abbreviations: LA, leaf area; RDW, root dry weight; RFW, root fresh weight; RL, root length; RSR, root–shoot ratio; SDW, shoot dry weight; SFW, shoot fresh weight; SL, shoot length.

altitudes in the area are more favorable for maximizing SFW. The average dry shoot biomass of *C. sativa* increased from 4.68 gm/plant in 2019–5.98 gm/plant in 2020 (Table 7). This indicates that the sowing year plays a significant role in determining the biomass production, with 2020 showing a higher biomass compared to 2019 (Table 7). The difference in biomass production observed between growing years can be attributed to variations in soil moisture levels. Specifically, fluctuations in nutrient availability (OC, nitrogen, sulfur, and phosphorus), soil pH, and water retention across seasons likely influenced plant growth dynamics, resulting in measurable changes in biomass output (Table 4). There is a significant increase in shoot dry biomass as altitude rises from 1379.1 masl (Emba Rufael) to 2625.6 masl (Seret) (Table 8 and Figure 5B). This highlights the importance of altitude as a determinant of *C. sativa* biomass production, with higher altitudes generally favoring greater biomass. Several studies support the finding that altitude and associated climatic conditions significantly influence *C. sativa* biomass production [42, 43].

One of the important mechanisms for plants responding to their environments is allocation of resources between shoots and roots to optimize resource uses [12]. In the present study, study sites (tabiyas), sowing date, and sowing year significantly affected camelina shoot and root biomass (Table 6, Figure 5A,B and Figure 6B). This suggested that due to the changes in soil fertility, precipitation, and temperature of the different agroecologies, there was a difference in growth performances. Camelina plants grown in highland (District Dogua'Tembien) had increased shoot and root biomass compared to those grown in the other agroecologies (Figures 5B and 6B). This pattern aligns with findings in camelina (*C. sativa*), where plants prioritize root over shoot growth under resource-limited conditions, as demonstrated by Kim et al. [44]. However, Waraich et al. [45] reported proportional root-shoot growth in camelina cultivated in the study sites having midland agroecology, highlighting the species' phenotypic plasticity in response to environmental gradients. These discrepancies underscore camelina's sensitivity to environmental factors, including moisture availability, temperature regimes, and edaphic conditions. For instance, Ahmed et al. [12], Kim et al. [44], and Raza et al. [46] collectively demonstrated that reduced agroecological elevation and moisture scarcity disproportionately decrease shoot biomass relative to roots: a stress adaptation strategy. The present study's results from 2019 to 2020 cultivation years have elucidated this dynamic. June sowing produced taller plants with higher shoot biomass but less root development, likely due to favorable moisture and moderate temperatures early in the season. In contrast, July sowing was not as optimum due to the short-lasting moisture as rainfall stops in early September in Tigray. This temporal variability confirms camelina's adaptive capacity to optimize biomass partitioning under contrasting abiotic stresses, as evidenced by its differential responses to sowing dates and agroecological gradients [12].

Root fresh biomass of *C. sativa* was significantly affected by the study sites (Tabiyas), sowing year, sowing date, and their interaction (Table 6). The highest average RFW is 10. 89 gm/plant and the lowest, 0.81 gm/plant, were recorded in Tabiyas Seret and Emba Rufael, respectively (Table 8 and Figure 6A). As the altitudinal variation increases from 1379.1 m.a.s.l. (Tabiya Emba Rufael) to 2685 m.a.s.l. (Tabiya Seret), RFW increases significantly. *C. sativa*

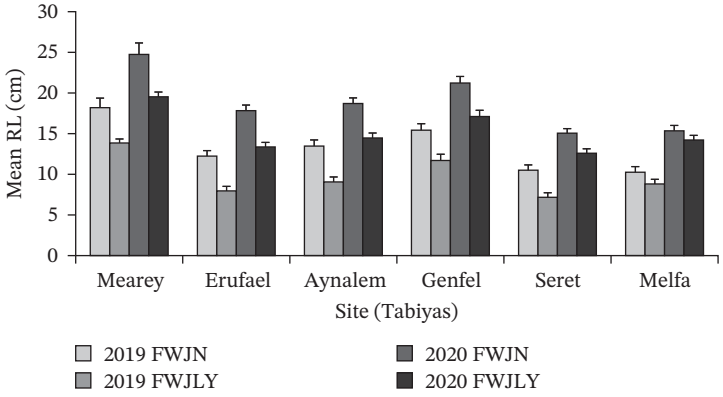


FIGURE 4 | Mean root length of *C. sativa* in different sowing date and Study sites (Tabiyas) of Tigray.

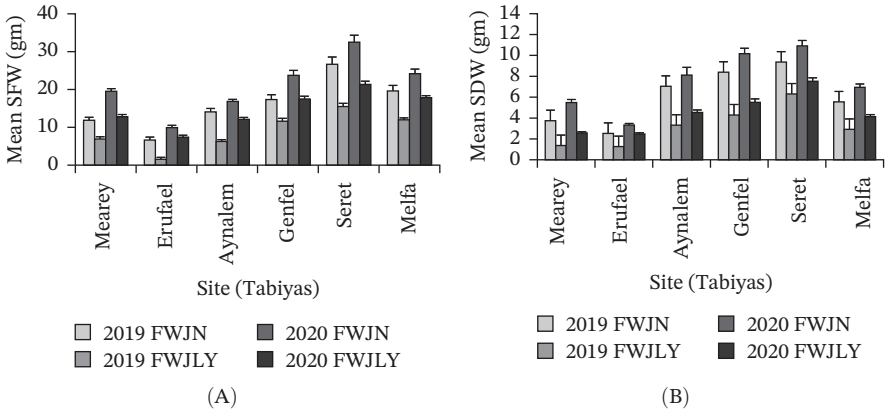


FIGURE 5 | Shoot fresh weight (A), shoot dry weight (B).

plants sown in June 2020 have the highest RFW, compared with those sown in July 2019. (Figure 6A).

The highest (0.58 g) root dry biomass of *C. sativa* was observed in Tabiya Seret, and the lowest (0.14 gm) in Tabiya Mearey (Table 8). *C. sativa* grown in the higher and moderate altitudes and sown in June 2020 has significantly higher root dry mass compared to *C. sativa* grown in the lower altitudes was sown in July 2019 (Figure 6B). The sowing date significantly affected ($p \leq 0.05$) the root dry biomass of *C. sativa* in all study sites (Tabiyas) of the farmers' training centers of all Tabias (Table 5).

Results of our research discovered maximum camelina dry biomass due to early sowing (early June) in all study sites (Tabiyas) and decreased plant dry biomass accumulation with delayed sowing date (early July) in the two successive cultivating years (2019 and 2020). In the early sowing date (June), plant dry biomass increased faster than in the late sowing date (July), mainly due

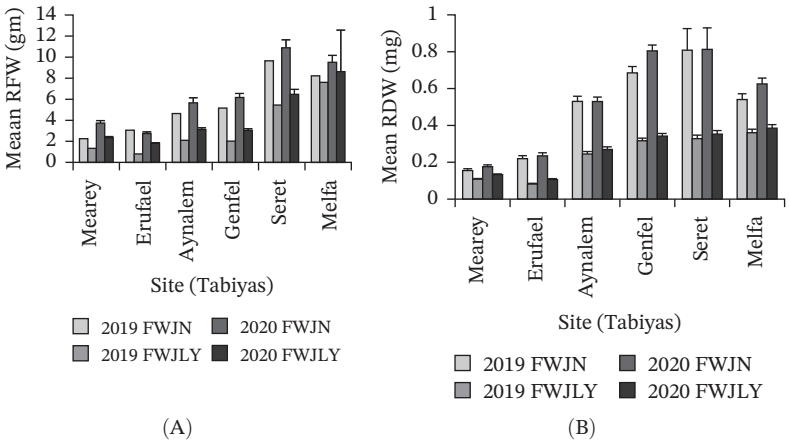


FIGURE 6 | Mean root fresh weight (A) and mean shoot dry weight (B) of *C. sativa* grown in two cultivating years.

to rapid LA development that received more rainfall thus producing more photosynthates used for plant growth and development. The present results are similar to Ghosh et al. [47], who reported a similar trend of plant growth in barley and grass pea grown under different sowing dates in different agricultural ecologies. Reduction in shoot and root dry biomass under delayed sowing date occurred due to suboptimum temperature and rainfall decreasing during the vegetative growth phase, as leaf development and dry matter accumulation greatly depend on temperature and rainfall.

3.3.4 | Root Shoot Ratio

The early-sown (June) *C. sativa* plants had a higher root–shoot ratio (0.080) than the late-sown (July) ones in all study sites (Tabiyas) (0.077) (Table 5, Figure 7). Sowing year has significantly affected the root–shoot ratio of *C. sativa* at the confidence level of $p \leq 0.05$. For the sowing year, *C. sativa* plants cultivated during the 2019 growing season resulted in a higher root–shoot ratio (0.089) than the plants grown in the 2020 growing season (0.068) (Table 7). Based on the site location in which *C. sativa* is cultivated, the highest and lowest root–shoot ratios were observed in Tabiya Seret (0.27) and Mearey (0.27), respectively (Table 8).

It is known that the development of root and shoot systems is affected by the availability of nutrients and moisture [48]. According to Pavlista et al. [49], availability of soil nutrients and moisture affected for a longer time critically affected the growth of camelina and two other crops. A similar study conducted by Tokozwayo et al. [50] emphasized that crops grown in lowlands accumulate more carbohydrates and other biomolecules in their roots. This plays an important role in these crops having a higher root–shoot ratio than the crops grown in the midlands and highlands. Water deficiency significantly decreased photosynthetic rate, resulting in a decrease in food supply to the shoot portion, which could be in effect due to the change in root–shoot ratio [50].

3.3.5 | LA (cm^2)

LA is an essential parameter that shows the incremental phase of crops in agriculture. Analyzed data indicated that LA was significantly ($p \leq 0.05$) influenced by study sites (Tabiyas), sowing date, and all their interactions (Table 6). The highest and lowest LAs were recorded in Tabiya Genfel (26.789 cm^2) and Mearey (10.851 cm^2), respectively (Table 8). Regarding the sowing date, camelina plants sown in early June (17.45 cm^2) have developed larger leaves when compared to those sown in early July (16.047 cm^2) (Table 5). A greater LA (20.952) was observed in the second-round cultivation year (2020) (Table 7). Camelina plants that were sown in the early week of June 2020 at Tabiya Genfel had the largest LA, while those sown in the early week of July 2019 at Tabiya Emba Rufael had the smallest LA (Figure 8). Results of the present study noted that the highest LA was observed in the first planting date (early June), and LA decreased with late planting in all experimental sites (Tabiyas). These outcomes are in accordance with the findings of Ghaffarian et al. [51], who described that in early planting maximum LA is due to optimum utilization of resources and high photosynthetic activity. According to the findings of Awad et al. [52], reduction in growth

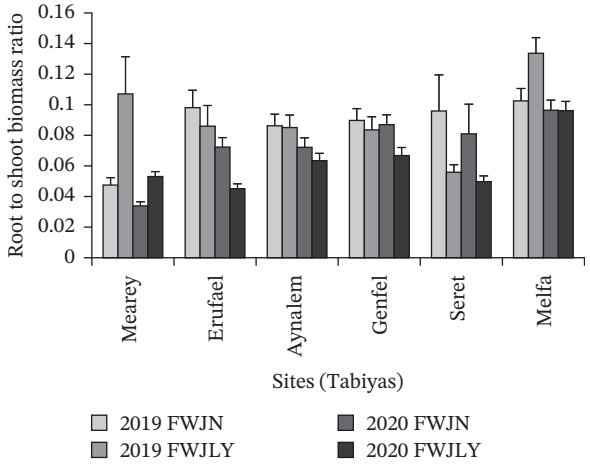


FIGURE 7 | Root–shoot biomass ratio.

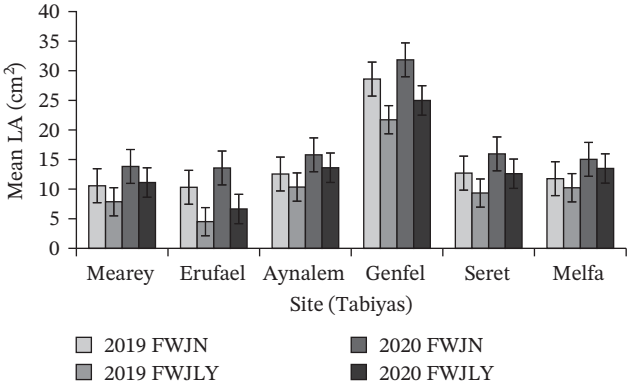


FIGURE 8 | Leaf area of *Camelina sativa* grown in two successive experimental years. Abbreviations: FWJN, first week of June; FWJLY, first week of July; LA, leaf area.

duration is responsible for decreased LA because day duration is reduced and less amount of radiation is absorbed, leading to less photosynthetic efficiency. According to the present results, as the altitude of the experimental sites increased, the expansion of the LA also increased. This may be due to the availability of low rainfall and high temperature at low altitude (lowlands) compared to the highlands. Water deficit slows down the photosynthetic process, accelerates yellowing, and induces faster aging of leaves, which causes a reduction in LA. Similar findings were reported by Hussain et al. [53] in cereals.

3.3.6 | Phenology: Flowering Date and Growth Degree of Days to Flower

The flowering date of *C. sativa* was influenced by study sites (Tabiyas), sowing date, and sowing year (Table 9). In the growing seasons of 2019 and 2020 across different study sites (Tabiyas) of Tigray, days to emergence were 5 days after sowing to flowering (DASF) during both seasons. *C. sativa* plants showed variation in days to anthesis at all study sites (Tabiyas) during both growing seasons and sowing dates. At Yechila Abergele district (Tabiya Mearey), a minimum of 32 and 44 days to reach 50% and 90% flowering, respectively, was documented for plants sown in the first week of July during the 2019 growing season. Camelina

TABLE 9 | Number of days to 50% and 90% flowering and growth degree of days to flowering.

	Days to 50% to flower				Days to 90% to flower and growth degree of days to flower (GDDF)							
	Year (2019)		Year (2020)		Year (2019)				Year (2020)			
					June		July		June		July	
Sites (Tabiyas)	June DASF	July DASF	June DASF	July DASF	DASF	GDDF	DASF	GDDF	DASF	GDDF	DASF	GDDF
Mearey	40	34	35	32	49	1290.6	44	955	45	1015.6	46.	1037.8
E/Rufael	42	36	40	37	52	1281.7	49	1041.4	48	1081.25	50	1125.45
Aynalem	55	37	55	42	69	1053.15	50	1041.9	65	1021.7	54	1127.4
Genfel	56	46	60	48	71	1134.15	61	1028.4	70	1098.2	60	927.35
Seret	75	70	73	65	85	961.5	84	902.7	83	1020.25	78	918.8
Melfa	72	67	70	61	84	950.75	82	878.7	80	873.05	75	895.8

Abbreviations: DASF, number of days after sowing to flower; GDDF, growth degree of days to flowering.

plants sown in June 2019 in the Degua' Temben district (Tabiya Seret) took a maximum of 75 and 84 days to reach 50% and 90% flowering, respectively. Regarding growth degree days to flower (GDDF), a maximum (1290.6) and minimum (873.05) to reach 90% flowering were documented in the Yechila Abergele district (Tabiya Mearey) and Degua' Temben district (Tabiya Melfa), respectively (Table 9; Figure 2).

These findings align with research conducted in Pakistan and China by Chen et al. [54], who confirmed variability in phenological development (flowering) due to differing agroecologies and temperature regimes. Crop growth and development rates accelerate with increasing temperature in most environments, directly affecting flowering phase duration and seed yield [55]. Similarly, other researchers found that crops in study sites having higher elevations with lower temperatures take more days to flower, while those in lower elevations with higher temperatures (warmer climates) complete flowering faster [56].

Phenology metrics like flowering date and GDD to flower indicate the transition from vegetative to reproductive phases, where prolonged vegetative duration in highlands enhances growth traits such as shoot and RLs, fresh and dry weights, LA, and root–shoot ratio [57]. Earlier flowering in lowlands shortens the vegetative window, potentially limiting biomass accumulation, while higher GDD to flower allows more time for growth optimization. Delayed flowering correlates with extended vegetative growth, boosting SDW and LA by allocating more resources prereproduction, with higher GDD positively linking to root–shoot ratio and overall biomass via improved crop growth rates [57]. In agroecology studies, these ties explain environmental impacts on yield potential, as late flowering prioritizes vegetative traits [58].

Higher temperatures in lowland study sites like Yechila Abergele (Tabiyas Emba Rufael and Mearey) accelerated flowering (minimum 32–44 DASF), shortening the vegetative phase and restricting resource allocation to SL/RLs, fresh/dry weights, LA, and root–shoot ratios via faster metabolic rates and reduced photosynthesis duration. In contrast, cooler highland sites (Degua Temben, maximum 75–84 DASF, 1290 GDDF) extended vegetative growth through slower GDDF accumulation, enhancing biomass via prolonged cell division/expansion and higher resource partitioning prereproduction. Sowing date and year effects likely modulated this via photoperiod-temperature interactions, prioritizing vegetative sinks before floral transition.

Field variability across Tigray tabiyas confounds isolating temperature from soil moisture or photoperiod effects on GDDF-flowering links to vegetative traits, with only 2 years (2019–2020) limiting climate trend detection. Measurements aggregated at 50%/90% flowering may overlook intraplant variability, and lack of controlled experiments restricts causal inference between phenology and growth metrics like root–shoot ratio [58]. Genotypic uniformity of *C. sativa* assumes minimal cultivar influence, potentially overlooking local adaptations.

Conduct multiyear trials with temperature-controlled chambers to dissect GDDF effects on vegetative biomass under Tigray gradients, incorporating genomics for flowering linked to SDW. Integrate remote sensing for finer-scale phenology-growth mapping across elevations, and test delayed sowing/manipulation for optimizing root–shoot ratios in oilseed agroecology. Longitudinal studies should model GDDF thresholds for vegetative yield stability amid climate shifts.

4 | Conclusions and Recommendations

4.1 | Conclusions

This study evaluated *C. sativa* vegetative growth responses to agroecological gradients (lowland, midland, and highland) and sowing dates across Tigray tabiyas over 2019–2020, addressing objectives to identify optimal conditions under semi-arid, rainfed systems.

Increasing agroecological elevation positively influenced shoot and RLs, shoot/root biomass, shoot–root ratio, and LA, with the highest values recorded in the Degua Tembien (highlands). Conversely, RL increased with decreasing elevation. Earlier sowing (June) enhanced these vegetative parameters across sites. These patterns suggest that highland agroecologies combined with early sowing promote superior vegetative development, implying that Degua Tembien is a promising area for *C. sativa* cultivation in Tigray. Findings highlight the interactive effects of environment and management on growth traits, informing targeted strategies for oilseed integration in the Ethiopian highlands.

4.2 | Recommendations

Based on the findings of this study, which primarily focus on vegetative growth parameters of *C. sativa* under Tigray (Ethiopian) agricultural lands, the following recommendations are proposed.

1. Tigray farmers may consider sowing *C. sativa* in early June at the onset of the rainy season to potentially optimize vegetative growth, pending confirmation through yield trials.
2. Highland agroecologies appear to enhance vegetative growth performance of *C. sativa*; farmers in suitable areas might prioritize these locations, subject to further validation with productivity data.
3. Additional research is needed on crop productivity.

Author Contributions

Gebremedhn Yohannes contributed to project conception, site selection, data collection, data analysis, and manuscript preparation. Berhanu Abraha Tsegay participated in project conception, site selection, project administration, and manuscript preparation (reviewing and editing). Leul Kidane assisted with site selection and field data collection. Yemane G. Egziabher supported the project through laboratory data generation. Dawit Kidane contributed to the language edition and drew figures for the manuscript. Tadesse Beyene assisted with reviewing and editing the taxonomic status of the study plant (crop).

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Consent

All authors certify that they give their consent to publish the paper if accepted.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

All data used in this study will be available upon a prior request from the corresponding and first authors.

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