

Effect of Water Stress and Cabbage Aphid Feeding on Ethiopian Mustard *Brassica carinata* Physiology

Amlsha Mezgebe ^{1,✉}, Ferdu Azerefegne ², Alemu Dessa ²

1. Plant and Horticultural Sciences, Mekelle University, Mekelle, ETH

2. Plant and Horticulture Sciences, Hawassa University, Hawassa, ETH

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Abstract

Water deficit represents a critical abiotic constraint that impairs fundamental physiological processes in plants. Water deficit as a single stressor influences aphid's performance indirectly through changes in plant physiology. The present study was conducted in a greenhouse to investigate the effects of water stress and cabbage aphid (*Brevicoryne brassicae*) feeding on the physiology of Ethiopian mustard (*Brassica carinata*). In addition, the study examined how drought-induced changes in host plant physiology influence aphid performance. A factorial experiment was conducted to evaluate the individual and combined effects of drought stress and aphid infestation. Four levels of drought stress and two aphid infestation treatments were arranged in a randomized complete block design with 10 replications. Water stress had a significant effect on Ethiopian mustard physiology and cabbage aphid performance. Transpiration rate, photosynthetic rate, and stomatal conductance of *B. carinata* leaves decreased significantly as water stress increased. Transpiration rate, photosynthesis, and stomatal conductance of *B. carinata* leaves were reduced by 55.62%, 61.26%, and 63.53% in water-stressed plants. On the other hand, feeding by cabbage aphid significantly reduced transpiration rate, photosynthesis, and stomatal conductance on *B. carinata* leaves. Under conditions of water deficit, *B. brassicae* demonstrated significantly higher fecundity and an accelerated population growth rate (r_m). The findings suggest that drought stress has the potential to change the physiology of the *B. carinata* plant and cabbage aphid population dynamics. The interaction effect of water stress and aphid feeding significantly influenced the photosynthetic rate, transpiration rate, and stomatal conductance of *B. carinata* plants.

Categories: Disease & pests of crops, Field & Horticultural crops sustainable production, Sustainable climate smart agriculture

Keywords: photosynthesis, transpiration, intrinsic rate of increase, cabbage aphid, ethiopian mustard

Introduction

Climate change is having a significant impact on all biological entities living on Earth. The climate change projections made in the past indicate that the temperature and greenhouse gas levels on the globe are increasing from time to time [1]. Increasing drought, rising temperature, and other weather extremes resulted in a steady rise in the frequency and intensity of insect infestations, while at the same time increasing the unpredictability of outbreaks [2,3]. Drought is a pivotal environmental stressor that fundamentally alters plant physiological performance, thereby restricting growth and development while exerting a significant negative impact on photosynthetic capacity [4] and directly influencing physiological processes, leading to decreased growth, changes in resource allocation, and changes in secondary metabolite profiles in most terrestrial crops [5,6]. Drought-stressed plants exhibited higher nutritional quality than well-watered plants, evidenced by elevated amino acid concentrations and increased osmotic pressure within the sieve

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elements [6]. Under drought and waterlogging conditions, the chemical composition of plants is altered [6]. Water stress elevates the concentrations of soluble proteins, carbohydrates, and free amino acids within plant tissues [7], creating physiological conditions that may encourage the proliferation of phloem-feeding insects. Drought stress can significantly influence plants' photosynthetic activities by inducing leaf chlorosis, triggering stomatal closure, and reducing overall carbon assimilation efficiency [8,9]. Water deficit triggers species-specific physiological shifts in host plants, exerts effects on the nutritional quality and defense profiles available to distinct herbivore feeding guilds [10]. The effect of herbivorous insect feeding on photosynthesis, transpiration rate, and leaf stomatal conductance is greatly variable depending on the particular insect-plant interaction [11]. Phytophagous insects impair host plant photosynthesis through multiple mechanisms: the reduction of assimilatory surface area via leaf deformation, the degradation of chlorophyll a and b pigments, and the physical occlusion of stomata by honeydew deposits [12]. Defoliating insects cause significant reductions in photosynthetic surface area; however, plants may exhibit a plastic response by up-regulating photosynthetic rates per unit area in undisturbed tissues to compensate for the lost biomass [13,14]. In *Arabidopsis thaliana*, feeding by *Trichoplusia ni* reduces stomatal conductance in damaged areas, which indirectly inhibits photosynthetic efficiency in the remaining intact leaf tissues [15]. On the other hand, photosynthesis of the host plant can be strongly lowered by phloem-feeding insects like aphids [12]. Water-limited conditions in host plants significantly affect the fitness of phloem-feeding insects, with changes in turgor pressure and nitrogen concentration directly or indirectly regulating aphid growth and survival. Moderate water deficit indirectly modulates aphid performance by altering host plant physiology; specifically, the suppression of protein metabolism and accelerated amino acid synthesis lead to an elevation in soluble nitrogen levels [6,16]. An elevation in phloem nitrogen, primarily driven by an increased concentration of free amino acids, enhances the nutritional quality of the host plant, thereby facilitating the rapid growth and elevated reproductive rates of phloem-feeding insects such as aphids [17]. The impact of drought stress on aphid performance is inconsistent depending on the intensity of the water deficit as well as the host plant and the aphid species involved [18-20]. Until now, some studies have been reported on the impact of water deficit and aphid feeding on photosynthesis of different Brassica species. However, there have been no investigations on the influence of drought stress and aphid feeding on the physiology of Ethiopian mustard, *Brassica carinata*. Therefore, this investigation was planned to: (1) study the effects of water stress and aphid feeding on *B. carinata* physiology by measuring photosynthetic rate, transpiration rate, and stomatal conductance; (2) study the effect of water stress on cabbage aphid *Brevicoryne brassicae* performance.

Materials And Methods

Host plant and aphid

Ethiopian mustard (*B. carinata* A. Braun) var. Yellow Dodola was used as the experimental plant material. Seeds were sown in 5-L plastic pots containing a homogenized potting medium composed of loamy soil, sand, and compost in a 2:1:1 ratio (v/v/v), respectively. The growth medium was thoroughly mixed before pot filling to ensure uniformity among experimental units. Five seeds were sown per pot, and after seedling emergence, seedlings were thinned to two healthy and uniform seedlings per pot to maintain consistent plant density. The plants were grown under greenhouse conditions throughout the experimental period and managed according to standard agronomic practices to ensure normal growth and development. Colonies of cabbage aphid (*B. brassicae*) were established from individuals collected from naturally infested Brassica plants in the field. The aphids were subsequently reared on healthy, Ethiopian mustard plants in a greenhouse maintained at $28 \pm 1^\circ\text{C}$ and 65% relative humidity. To minimize the influence of field-acquired factors and ensure colony acclimatization to greenhouse conditions, the aphids were maintained for at least five consecutive generations under these conditions before being used in the experiments.

Experimental design

The experiment was conducted in a greenhouse using a 4×2 factorial arrangement in a Randomized Complete Block Design (RCBD). The first factor consisted of four drought stress levels, and the second factor comprised two aphid infestation treatments (aphid-free and aphid-infested plants), resulting in eight treatment combinations. Treatments were randomly assigned within each block to account for potential spatial variation within the greenhouse and replicated ten

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times. Water availability was maintained depending on the soil bulk density and it included: (1) water-stressed plants with water content at 40% field capacity (WS), (2) intermittent moderate stress (IMS) where plants were allowed to fluctuate between stress levels. Pots were subjected to drying to 40% FC and then re-watered to a moisture level of 80% field capacity, (3) well-watered plants with water content at 80% field capacity (WW), and (4) plants with water content at field capacity (FC). Three seeds were sown in plastic pots measuring 14 cm in height, with a top diameter of 15 cm and a bottom diameter of 10 cm. Seedlings were thinned to a density of one plant per pot 1 week after germination to ensure consistency across experimental units. Twenty-one-day-old *B. carinata* individuals were randomly allocated to one of four distinct moisture regimes: 600 mL water/week (FC), 375 mL water/week (WW), 250 mL water/week (IMS), and 150 mL water/week (WS), each plant were watered three times per week. After drought treatments were established, plants in the aphid treatment were infested with 15 adult cabbage aphids per plant to assess the combined effects of drought stress and aphid feeding. Apterous (wingless), actively feeding adults of uniform size were selected from a greenhouse-maintained stock colony and gently transferred using a fine camel-hair brush onto the abaxial surface of fully expanded leaves to minimize physical injury. Aphids were immediately introduced onto the designated experimental plants and allowed to establish naturally. All infested plants were enclosed in insect-proof cages to prevent escape and cross-contamination between treatments.

Plant physiology measurements

Gas exchange parameters, including the net photosynthetic rate (Pn), stomatal conductance (gs), and transpiration rate (E), were quantified using an LCA-4 ADC portable infrared gas analyzer (Analytical Development Company, Hoddesdon, England). Measurements were performed on intact, fully expanded second leaves during solar noon (between 11:00 a.m. and 3:00 p.m.) and data were recorded from five representative plants per treatment from each experiment. Within the leaf cuvette, the following parameters were maintained or monitored: a leaf surface area of 6.5 cm², an ambient CO₂ concentration (Cref) of 340 µmol mol⁻¹, and a molar gas flow rate of the leaf chamber (U) of 3,400 µmol s⁻¹. The ambient pressure (p) was recorded at 829 mbar, while the Photosynthetically Active Radiation (PAR) at the leaf surface reached a maximum of 2,250 µmol m⁻² s⁻¹. During the sampling period, the leaf chamber temperature (Tch) fluctuated between 27°C and 37°C, with corresponding mean leaf temperatures ranging from 25°C to 38°C. For each replication, stable readings were recorded at 1-minute intervals over a 5-minute duration.

Developmental, survival, and reproductive period

After 1 week of exposure to the drought stress treatments (seedlings at 28 days after emergence), each plant was infested with five apterous adult cabbage aphids (*B. brassicae*) obtained from a greenhouse-maintained stock culture. Infested plants were immediately enclosed in insect-proof cages to prevent aphid escape and cross-contamination among treatments. After 24 hours, the adult aphids were removed, and 20 newly produced first-instar nymphs were retained on each plant for the experiment. Each treatment was replicated 10 times. Following the establishment of 20 first-instar nymphs on each experimental plant, aphids were monitored daily throughout their development and reproductive period. Observations were conducted at 24-hour intervals to record survival, development, and reproductive performance. The pre-reproductive period was defined as the time (days) from the birth of a first-instar nymph to the production of its first offspring. Survival rate (%) was calculated as the proportion of nymphs that successfully reached adulthood relative to the initial number of nymphs established on each plant. Mortality (%) was determined as the proportion of nymphs that died before reaching adulthood. Upon adult emergence, individual aphids were observed daily, and the number of offspring produced by each female was recorded and removed after counting. Fecundity was expressed as the total number of offspring produced per female during her reproductive lifetime. The reproductive period was calculated as the number of days between the production of the first and last offspring by an adult female. Adult longevity was determined as the duration (days) from adult emergence to death. Lifespan was calculated as the total duration (days) from the birth of the first-instar nymph to death of the adult. All observations were continued until the death of the last surviving aphid.

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Population density

Ten newly emerged apterous adult aphids obtained from the stock culture were introduced onto plants subjected to each water-stress treatment. The aphids were maintained on the plants for 15 days after infestation to allow population establishment and development. At the end of the experimental period, the numbers of nymphs, winged adults, and wingless adults were recorded, and the total aphid population was determined. These data were used to assess the effect of water stress on the population density of the cabbage aphid.

Statistical analysis

Photosynthetic rate, transpiration rate, stomatal conductance, and cabbage aphid density were subjected to Analysis of Variance for a RCBD using SAS (Version 9.4). Treatment means were compared using Tukey's Studentized Range (Honestly Significant Difference) test with a significance level of $P < 0.05$.

Age-specific life table parameters including the intrinsic rate of natural increase (r) were estimated by solving the Euler-Lotka Equation [21].

$$\sum l_x m_x e^{-r_m x^*} = 1$$

Where

$$L_x = \frac{l_x + l_{x+1}}{2} \text{ and } x^* = \frac{x_l + x_{l+1}}{2}$$

Where l_x represents the age-specific survival rate (the proportion of the original cohort surviving to age x), m_x is age-specific fecundity (the mean number of female offspring produced per female at age x), and r_m is the population's intrinsic rate of increase. In addition, net reproductive rate ($R_0 = \sum L_x m_x$), population doubling time ($DT = \ln 2 / r_m$), generation time ($T = \ln R_0 / r_m$), and finite rate of increase ($\lambda = \exp. (r_m)$) were determined.

Results And Discussion

Water-stress and aphid feeding effects on *B. carinata* physiology

The physiological response of *B. carinata* to water stress exhibited a significant variation among water treatments ($P < 0.0001$) (Table 1). Increased transpiration rate, photosynthetic rate, and stomatal conductance were recorded in plants grown under FC treatments, and the lowest rates were recorded in plants grown under WS treatments (Table 1). Transpiration rate of *B. carinata* was reduced by 55.62% and 19.67% in WS and IMS plants, and increased by 4.67% in FC plants relative to well-watered control plants, respectively. On the other hand, photosynthetic rate was reduced by 61.26% and 23.45%, and increased by 16.52% at WS, IMS, and FC treatments, respectively. The stomatal conductance of *B. carinata* leaves was reduced by 63.53% and 27.78% in WS and IMS plants, and increased by 22.73% in FC plants, respectively. The current study revealed that the physiological parameters of *B. carinata*, namely photosynthetic rate, transpiration rate, and stomatal conductance, decreased with increasing water stress. Photosynthesis and transpiration rate of *B. carinata* were reduced significantly under water-stressed plants. As shown in recent studies, drought stress markedly reduces the efficiency of photosynthesis and the rate of transpiration in crops like naked oat and medicinal plants such as *A. lancea* [22,23]. Plants grown under water stress close their stomata to conserve the available water for growth and development, and this leads to a reduction in photosynthesis and stomatal conductance by directly decreasing gas exchange. Closing the stomata under water stress reduces the flow of water vapor out of the leaf, which leads to a reduction in transpiration rate. Water stress decreased stomatal conductance of *B. carinata* significantly, which is consistent with earlier observations by Hu et al. [24] on yellow horn and Zhang et al. [22] on naked oat, who reported that stomatal conductance was reduced under drought stress. The stomatal conductance of leaves in crop plants is

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reduced under water stress to reduce water loss, prevent dehydration, and improve transpiration efficiency. Water stress has been shown to significantly reduce stomatal conductance, photosynthetic rates, and transpiration in various crops, including potato [25], naked oat [22], winter wheat [26], and sweet potato leaves [27].

Cabbage aphid *B. brassicae* feeding significantly reduces the transpiration rate, photosynthetic rate, and stomatal conductance of *B. carinata* leaves (Table 7). The transpiration rate in aphid-infested plants was reduced by 19.89%, 8%, 13.84%, and 10.75% on WS, IMS, WW, and FC plants, respectively, as compared to aphid-free plants under the respective water treatments. The highest reduction in transpiration rate was recorded in plants grown under water-stressed treatments. The photosynthetic rate was reduced by 9.23%, 40%, 47.43%, and 25.5% on WS, IMS, WW, and FC plants, respectively. The highest reduction in photosynthetic rate was recorded in plants grown under well-watered treatments. Insect feeding reduces plant photosynthesis and transpiration rates through a combination of physical damage and the disturbance of water and nutrient transport throughout the plant. Feeding by *A. pisum* on pea plants and *Rhopalosiphum padi* on wheat plants was associated with a significant reduction in photosynthesis and transpiration rate [12]. Conversely, research by Pincebourde and Ngao [14] indicated that leaf damage actually stimulated photosynthesis, stomatal conductance, and transpiration in both apple and cotton plants. Another study by Huang et al. [28] demonstrated that feeding by *Aphis glycines* and *Rhopalosiphum padi* exerts a negative impact on the photosynthetic rates of soybean and wheat plants, respectively. In general, the effect of insect herbivory is characterized by highly plastic and complex interactions, governed by the specific species involved, the feeding guild and duration, and the ontogenetic stage of the host plant. Aphid feeding significantly suppresses photosynthetic and transpiration rates, as well as stomatal conductance. This decline results from the specialized feeding behavior of aphids, which extract nutrient-dense phloem sap. By depleting the products of carbon assimilation, herbivory induces a loss of photosynthetic pigments, specifically chlorophyll a and b, thereby impairing the plant's capacity to intercept light energy. According to Al-Aisae et al. [29], aphid-induced stress disrupted normal physiological functions, causing erratic stomatal behavior, a decline in chlorophyll content, and a significant reduction in photosynthetic efficiency. Additionally, the excretion of sugar-rich honeydew by aphids facilitates the colonization of black sooty mold on the leaf surface. This fungal layer acts as a physical barrier, reducing light penetration to the chloroplasts and consequently inhibiting the photosynthetic rate. Findings by Shannag [30] indicated that feeding by *Aphis fabae* on faba bean leaves significantly disrupted the host plant's physiological regulation, leading to a marked increase in stomatal conductance. Depending on the duration of feeding and the initial density of the aphid population, infested leaves exhibited a substantial rise in conductance levels, ranging from 51% to 224% compared to healthy plants.

On the other hand, the combined effect of water stress and aphid feeding significantly influenced the photosynthetic rate, transpiration rate, and stomatal conductance of *B. carinata* plants (Table 7). Transpiration rate, photosynthetic rate, and stomatal conductance were reduced by 58.74%, 33.11%, and 63.75% in WS aphid-infested plants, respectively, as compared to well-watered plants. In contrast, transpiration rate, photosynthetic rate, and stomatal conductance increased by 21.49%, 64.95%, and 52.5% in plants grown under FC, respectively, relative to well-watered control plants. A study by Al-Aisae et al. [29] revealed that the synergistic effect of drought and aphid infestation significantly increased the stomatal density, flavonoid content, electrolyte leakage, and proline accumulation across all drought levels, while simultaneously inhibiting photosynthetic activity. Aphid feeding and water stress significantly affected the leaf temperature of *B. carinata*, and the maximum leaf temperature was recorded under water-stressed treatments (32.5°C).

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Physiology measurements	Water treatments			
	WS	IMS	WW	FC
Aphid-free plants				
Transpiration rate (mmol m ⁻² s ⁻¹)	2.116±0.46 ^d	3.833±0.47 ^c	4.768±0.47 ^b	5.602±0.38 ^a
Photosynthesis rate (μmol m ⁻² s ⁻¹)	7.072±1.68 ^c	13.976±1.71 ^b	18.25±1.86 ^a	21.270±1.82 ^a
Stomata conductance (mmol m ⁻² s ⁻¹)	0.036±0.07 ^d	0.072±0.08 ^c	0.099±0.09 ^b	0.136±0.07 ^a
Leaf temperature (°C)	32.709±0.46 ^a	31.647±0.48 ^b	31.601±0.57 ^b	30.720±0.43 ^c
Aphid-infested plants				
Transpiration rate (mmol m ⁻² s ⁻¹)	1.695±0.40 ^d	3.526±0.53 ^c	4.108±0.42 ^b	4.991±0.51 ^a
Photosynthesis rate (μmol m ⁻² s ⁻¹)	6.419±1.55 ^c	8.382±2.01 ^b	9.596±1.14 ^b	15.829±1.47 ^a
Stomata conductance (mmol m ⁻² s ⁻¹)	0.029±0.05 ^d	0.063±0.79 ^c	0.080±0.07 ^b	0.122±0.10 ^a
Leaf temperature (°C)	32.469±0.67 ^a	31.870±0.91 ^b	31.017±0.54 ^c	31.098±0.41 ^c

TABLE 1: Effect of drought stress and aphid feeding on physiology measurements of *B. carinata* plants (mean ± SE)

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, 100% field capacity. Means within the rows sharing the same letter were not differ significantly ($P > 0.05$) according to Tukey's test

Biological parameters

Pre-reproduction, reproduction, adult longevity, and total lifespan of cabbage aphid under four water treatments are presented in Table 2. A longer pre-reproduction period (7 days) and a shorter reproduction period (8.6 days) of *B. brassicae* were recorded under FC treatments. The shortest pre-reproduction period (6.2 days) and the longest reproduction period (12.4 days) were observed under WS treatments. Drought stress significantly influenced the pre-reproduction and reproduction periods and adult longevity of cabbage aphid. However, there was no statistical difference among WS, IMS, and WW. Beetge and Krüger [25] observed that water regimes had no significant influence on the pre-reproductive, reproductive, or adult longevity periods of *Macrosiphum euphorbiae* on potato plants. Aphids feeding on highly drought-stressed plants developed more quickly, with a shorter pre-reproductive period and a

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prolonged reproductive phase without changing their total lifespan [31]. *Aphis fabae* produced more offspring on moderately and highly drought-stressed plants than on control plants [31]. The total developmental time of *A. colemani* was shorter on drought-stressed than on control plants [31].

The fecundity and longevity of cabbage aphids showed a statistically significant difference among water treatments (Table 2). Higher net fecundity of cabbage aphid was observed under WS (7.67 offspring/female), followed by IMS (6.8 offspring/female), WW (6.5 offspring/female), and FC (6.01 offspring/female). Cabbage aphid adults lived longer on WW plants, while longevity was shorter on FC plants. The fecundity of cabbage aphid increased with increasing drought stress, and the highest fecundity was recorded on WS plants. The accumulation of higher concentrations of soluble sugars, such as glucose and sucrose, in water-deficient plants enhances the nutritional quality of the host plant and promotes the growth, development, and reproduction of aphids. As indicated by Rahman et al. [31], the individual performance and fecundity of *A. fabae* were maximized on water-stressed hosts, whereas the lowest values were recorded on well-watered plants. Additionally, research by Tariq et al. [32] and Banfield-Zanin and Leather [33] demonstrated that moderate intermittent stress enhances the fecundity of *B. brassicae*, *M. persicae*, and *E. abietinum*. An enriched nutritional profile in drought-stressed plants enhances host suitability, thereby promoting aphid growth, development, and reproductive success.

Biological parameter	Drought regimes			
	WS	IMS	WW	FC
Pre-reproductive period (d)	6.2±0.66 ^b	6.0±0.00 ^b	6.8±0.66 ^a	7.0±0.00 ^a
Reproductive period (d)	12.4±0.94 ^a	10.6±1.44 ^{ab}	10.4±1.29 ^{ab}	8.6±0.74 ^b
Adult longevity (d)	13.8±1.14 ^a	12.4±1.34 ^a	14.4±0.94 ^a	9.8±0.69 ^b
Lifespan (d)	19.6±1.06 ^a	18±1.11 ^a	19.6±1.06 ^a	15.8±0.69 ^b
Fecundity (nymphs/female)	65.096±2.97 ^a	51.81±2.82 ^{ab}	48.09±3.27 ^b	38.41±2.63 ^b

TABLE 2: Biological parameter (mean ± SE) of cabbage aphid on *B. carinata* plants under different water stress

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, field capacity. Rows with the same letter were not significantly different based on Tukey's test at 0.05; d, days

The age-specific survivorship (l_x) denotes the probability that a newly produced individual will survive from birth to age x (Figure 1). There was no statistical difference among water treatments in survival rate from nymph to the adult stage (Figure 2). However, significant variability in the adult survival rate was found among water treatments. Higher adult survival rates were recorded under WS (46.1%) and WW (42.52%) water treatments. The lowest adult survival rates were observed under IMS (17%) and FC (13.3%) water treatments. The reduction in nymph survival rate under stressed plants may be due to decreased water content of the plant, which makes feeding difficult, and changes in plant chemistry that increase defensive compounds, which lead to reduced plant nutritional quality for the aphid. Beetge and Krüger [25]

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showed that the survival rate of *M. euphorbiae* nymphs was significantly lower on water-stressed potato plants compared with those on well-watered controls. A study by Nguyen et al. [34] revealed that severe water-deficit stress in potato plants resulted in reduced adult survival, abundance, and biomass of *M. euphorbiae*.

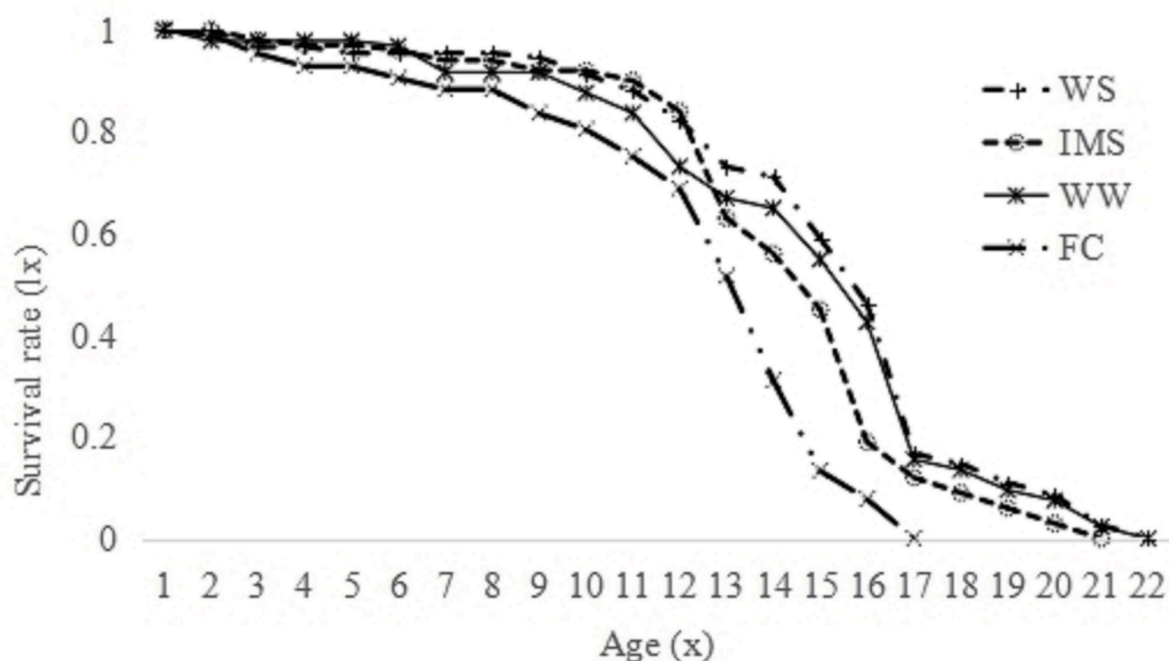


FIGURE 1: Age-specific survivorship (l_x) of cabbage aphid *B. brassicae* on four water treatments

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, field capacity

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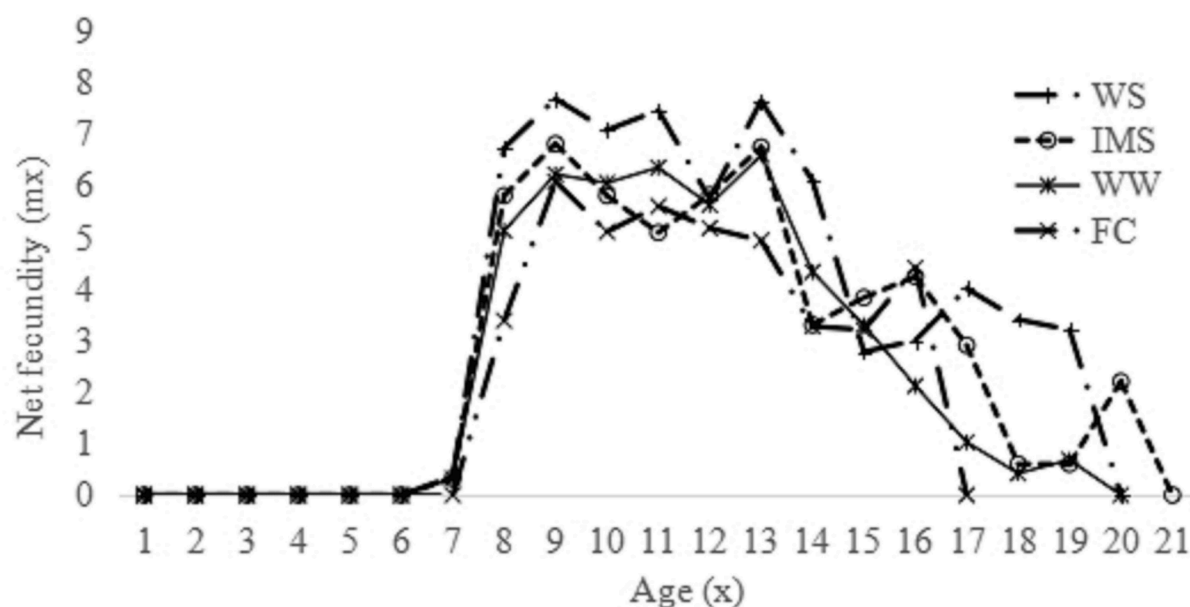


FIGURE 2: Net fecundity (mx) of cabbage aphid *B. brassicae* on four water treatments

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, field capacity

The highest total number of aphids was recorded on plants grown under IMS, and the lowest was recorded on plants grown under FC (Table 3). However, there was a significant variation in population density between IMS and WS plants. The presence of all aphid morphs on IMS plants resulted from the suitability of the nutritional quality of the plant for aphid production and multiplication. These results are similar to the findings of Banfield-Zanin and Leather [33], who reported increased total reproduction of *E. abietinum* under moderate intermittent stress. However, there was no statistically significant difference between WS and IMS drought treatments. Previous findings by Khan et al. [35] demonstrated that drought stress in *Brassica oleracea* plants led to an increase in the population size of the green peach aphid. According to the findings of Aslam et al. [36], drought conditions did not alter the total aphid abundance; however, they fundamentally changed the population demography, suggesting altered aphid development rates on drought-stressed plants.

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Drought	Aphid morphs			
	Nymphs	Apterous morphs	Alate morphs	Total
WS	1638.3±21.01 ^{ab}	134.58±7.39 ^{ab}	63.92±5.6 ^b	1836.8±21.84 ^{ab}
IMS	1877.7±25.31 ^a	196.75±10.64 ^a	99.75±12.5 ^a	2174.2±28.11 ^a
WW	1293.1±23.08 ^{bc}	140.00±8.72 ^{ab}	20.67±2.9 ^c	1453.8±24.53 ^{bc}
FC	910.2±20.55 ^c	98.58±6.19 ^c	23.83±4.8 ^c	1032.6±21.49 ^c

TABLE 3: Cabbage aphid population density (mean ± SE) 15 days after introduction to *B. carinata* plants under different water stress

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, field capacity. Means within the columns sharing the same letter do not differ significantly ($P > 0.05$) according to Tukey's test

Demographic parameter

The demographic parameters of cabbage aphid showed a statistically significant difference among water treatments (Table 4). All three key demographic parameters; the intrinsic rate of natural increase (r_m), the finite rate of increase (λ), and the net reproductive rate (R_0) showed significant growth as water-stress intensified. The maximum and minimum values for the net reproductive rate were recorded on WS and FC plants, respectively. Plants subjected to WS supported significantly higher r_m values, whereas the lowest rates were recorded on plants maintained at FC. Increased WS significantly reduced the population doubling time (DT) of *B. brassicae*, although no significant differences were observed between water-stressed and well-watered plants (Table 4). The shorter population DT observed under increased water stress suggests that *B. brassicae* populations were able to increase more rapidly on water-stressed plants. The shorter doubling time observed under increased water stress is consistent with the findings of Rahman et al. [31], who reported that drought-stressed sugar beet plants supported faster development and higher reproductive rates of *A. fabae*, resulting in enhanced aphid population growth. The authors suggested that drought-induced physiological changes in the host plant improved conditions for aphid performance. A significant negative correlation was observed between the aphid's reproductive parameters specifically fecundity and r_m and the water treatments. As the amount of water content increased in *B. carinata* plants, the intrinsic rate of increase (Figure 3) and fecundity of cabbage aphid decreased (Figure 4).

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Drought regimes	r_m	R_o	λ	T	DT
WS	0.373±0.10 ^a	46.18±2.44 ^a	1.453±0.12 ^a	10.24±0.31 ^a	1.857±0.22 ^b
IMS	0.360±0.14 ^a	35.41±2.42 ^b	1.434±0.16 ^a	9.89±0.62 ^{ab}	1.927±0.31 ^b
WW	0.354±0.13 ^{abb}	35.21±2.55 ^{bb}	1.424±0.16 ^{abb}	10.03±0.63 ^{ab}	1.962±0.32 ^{abb}
FC	0.329±0.11 ^b	24.03±2.26 ^c	1.391±0.13 ^b	9.59±0.64 ^b	2.107±0.28 ^a

TABLE 4: Demographic parameters (mean ± SE) of *B. brassicae* reared on *B. carinata* under varying water stress regimes

WS, 40% field capacity; IMS, allowed to fluctuate from 80% to 40% field capacity; WW, 80% field capacity; FC, field capacity. Means within the columns sharing the same letter do not differ significantly ($P > 0.05$) according to Tukey's test

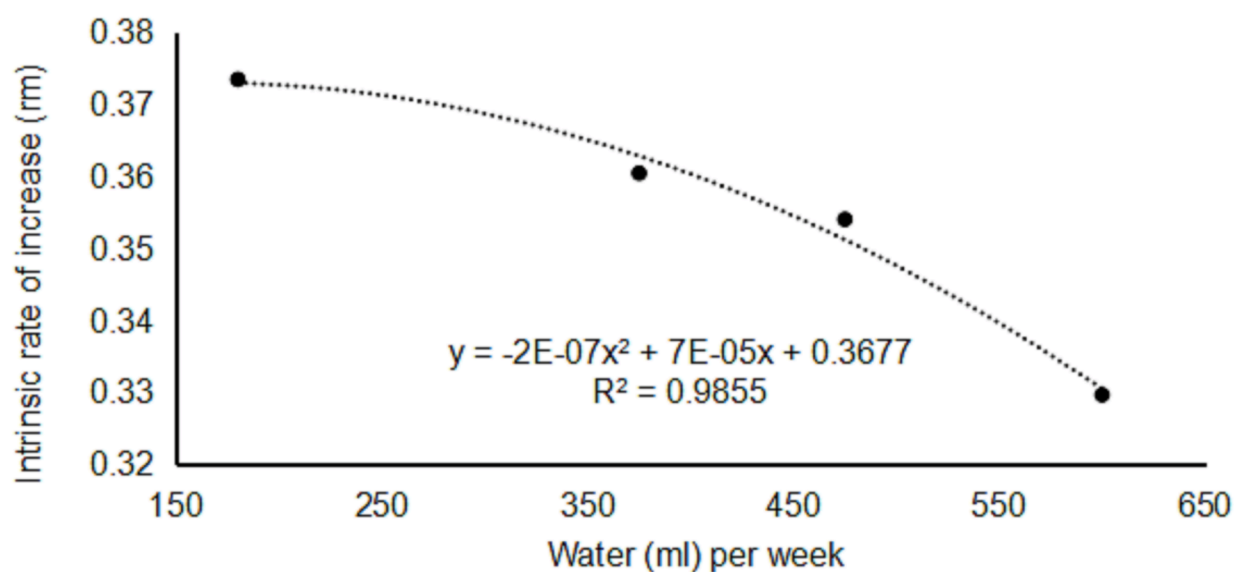


FIGURE 3: The relationship of intrinsic rate of increase (r_m) of cabbage aphid with watering regime

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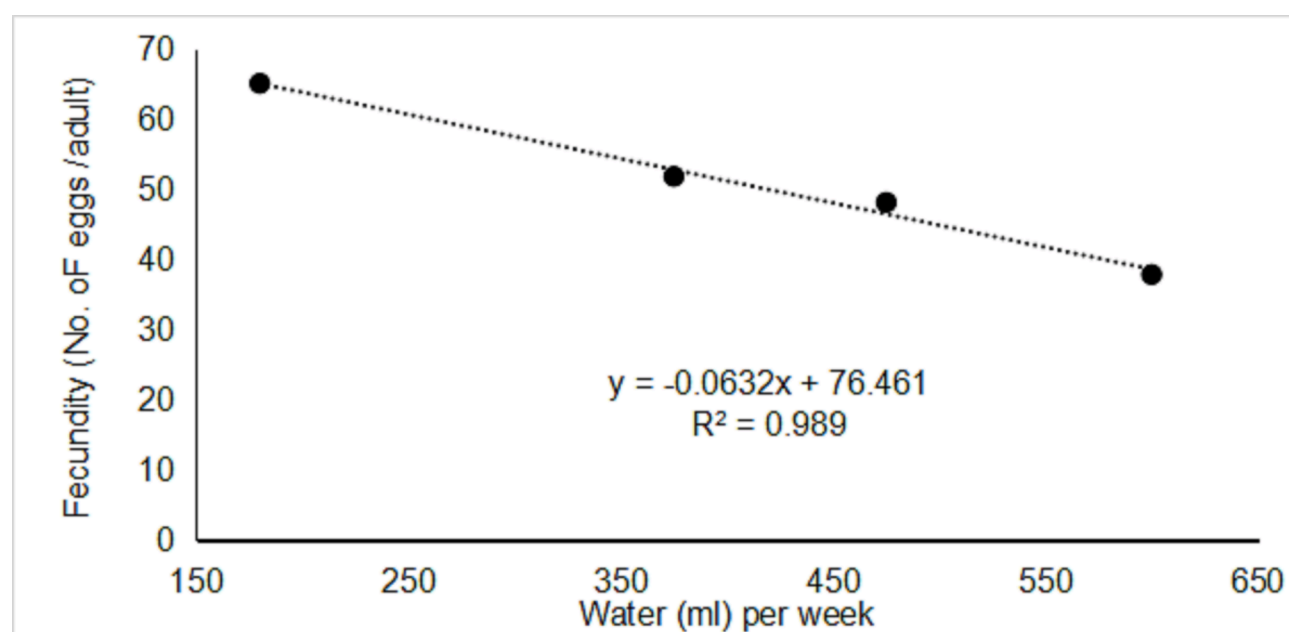


FIGURE 4: The relationship of the fecundity of cabbage aphid with watering regime

Both the intrinsic rate of natural increase (r_m) and the finite rate of increase (λ) for the cabbage aphid exhibited a positive correlation with increasing levels of water deficit. The highest r_m and shorter DT were recorded on water-stressed (40% FC) plants. The peak intrinsic rates of increase for both *B. brassicae* and *M. persicae* were observed under conditions of continuous moderate stress [32]. This positive response is likely driven by the dual effects of enriched plant nutritional status and the suppression of chemical or physical defenses under drought conditions. Findings by Rahman et al. [31] reported that a higher intrinsic rate of increase of *A. fabae* was recorded on moderately and highly drought-stressed rice plants. Additionally, a study by Banfield-Zanin and Leather [33] revealed that moderate intermittent stress increased r_m of adult *E. abietinum* but decreased it under severe drought stress levels (20% field capacity). In contrast, studies by Beetge and Krüger [25] indicated that mean generation time, intrinsic rate, and finite rate of increase, and doubling time of *M. euphorbia* on potato plants were not affected by water regime. Longer generation time of cabbage aphid was recorded on water-stressed plants. However, there was no statistical difference among WS, IMS, and WW plants. The longer generation time of the aphid is associated with changes in the nutritional quality of the sap and increased plant defence mechanisms. Banfield-Zanin and Leather [33] stated that severe drought stress (20% FC) significantly increased generation time and decreased the number of reproductive days of *E. abietinum*. Furthermore, the generation time of *E. abietinum* was reduced under moderate intermittent stress, with a subsequent increment in the number of reproductive days [33]. The particular result often counts on the intensity of the stress and the species of plant and aphid involved. The effect of drought stress on aphid performance is changeable [6,37], indicating that there is no general rule on the response of aphids towards drought-stressed host plants. The effect of drought stress on aphid growth and development can further depend on the timing and amount of water restriction practiced [32,38] and on specific interactions between aphid and host plant species [37,38]. The increment of nutritional quality which contains sugar and amino acid concentrations in the phloem sap on drought-stressed plants resulted in increased aphid performance [39,40].

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Conclusions

The current study provided basic information on the impact of water stress and aphid feeding on physiological parameters (photosynthesis, transpiration rate, and stomatal conductance) of Ethiopian mustard, *B. carinata*. Overall, our findings indicate that drought stress significantly influenced the physiological parameters of Ethiopian mustard plants, and reduced transpiration rate, photosynthetic rate, and stomatal conductance were observed in water-stressed plants. Feeding by cabbage aphid, *B. brassicae*, on Ethiopian mustard plants significantly reduced the transpiration rate, photosynthetic rate, and stomatal conductance. On the other hand, the interaction between drought stress and aphid feeding had a negative effect on physiological parameters of Ethiopian mustard. Drought stress had a positive effect on the development and population density of cabbage aphid, and higher fecundity, intrinsic rate of increase (r), and finite rate of increase, as well as a shorter doubling time, were recorded on water-stressed plants. The population of cabbage aphid was not influenced by drought stress, but drought stress resulted in an increase in aphid population density on the host. Therefore, we expect that with an increased frequency of drought stress anticipated under future climate change conditions, cabbage aphid outbreaks could be facilitated.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Amlsha Mezgebe, Ferdu Azerefegne, Alemu Dessa

Acquisition, analysis, or interpretation of data: Amlsha Mezgebe, Ferdu Azerefegne, Alemu Dessa

Drafting of the manuscript: Amlsha Mezgebe

Critical review of the manuscript for important intellectual content: Amlsha Mezgebe, Ferdu Azerefegne, Alemu Dessa

Disclosures

Plant subjects: All authors have confirmed that this study did not involve any herbarium specimen.

Human subjects: All authors have confirmed that this study did not involve human participants or tissue.

Animal subjects: All authors have confirmed that this study did not involve animal subjects or tissue.

Conflicts of interest: In compliance with [the ICMJE uniform disclosure form](#), all authors declare the following:

- **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work.
- **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work.
- **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

Data Availability Statements

The datasets (and/or code) supporting this study are available from the corresponding author upon reasonable request.

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