DETERMINATION OF THE CRITICAL PERIOD OF WEED CONTROL (CPWC) TO INCREASE THE YIELD OF BARLEY (*HORDEUM VULGARE* L.) CROP IN EGYPT

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Abstract. The purpose of this study was to determine the effect of different weed competition periods on the growth and yield of an Egyptian barley crop under field conditions, as well as to estimate the critical period of weed control (CPWC) in barley. The treatments were arranged in a randomized complete block design with three replications (i.e., plots 4 × 4 m each) and consisted of a quantitative series of both increasing duration of weed interference and length of weed-free periods. The measured morphological parameters of barley plants were greater in non-weedy barley fields than in weedy barley fields. The shoot height of non-weedy barley plants was significantly ($P < 0.05$) higher than that of weedy plants. After 75 DAE (Days After Emergence) of weed infestation, the maximum height and plant density were obtained. The biomass of barley plants and their associated weeds was gradually increased until 45 DAE, when barley biomass continued to increase, while weed biomass decreased. The maximum barley yield in the weed-free plots was 3.2 t ha^{-1} after 90 DAE, while it was 2.2 t ha^{-1} in the weed-infested plots after 75 DAE. Based on a 10% yield loss, the CPWC fell between 63 and 79 DAE, while a 5% yield loss fell between 41 and 102 DAE. Weed presence prior to and after the CPWC is not expected to reduce crop yield. As a result, weed removal at the CPWC is critical to allow plants to grow to their full potential without being hampered by competition and, hence, crop yield loss.
Keywords: *Barley, weed management, logistic model, yield loss, experimental design*

Introduction

Weeds compete with crops for moisture, nutrients, light, and space, resulting in significant yield losses, increased production costs, and crop quality degradation (Kalaitzandonakes et al., 2015). They compete with the crop plant throughout its life cycle, but weeds are more aggressive in a specific period during the crop cycle, when they can cause the greatest yield losses (Zafar et al., 2010; Menalled et al., 2020). Different crops necessitate different management activities, which can disrupt weed life cycles and prevent weed dominance (Bagheri et al., 2020). The timing of weed emergence and the duration of weed competition have a significant impact on crop yield, and studies have shown that just a few days of early crop growth relative to weeds can significantly shift the competitive balance in favor of the crop (Otto et al., 2009). Weeds have the greatest impact on crop growth during the critical period of weed control (CPWC); however, weed interference outside of this period had no effect on crop yield (Johnson et

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al., 2004). Furthermore, weeds that grow alongside crops deplete significant amounts of nutrients and soil moisture, resulting in poor crop growth (Shah, 2013).

The optimum plant population, which is determined by the cultivar, cropping system, planting date, and environmental conditions, may be used to achieve the goal of maximum yield and improved quality (Khan et al., 2021). Crop cultivation, floristic composition, and weed distribution, as well as biological traits of the crop such as growth rate and development during the growing season, maximum plant height, and leaf cover, all have a significant impact on crop competitiveness against weeds (Uremis et al., 2010). Furthermore, plant density makes the crop more competitive against weeds, while herbicides can be applied at lower rates (Simić et al., 2012). Integrated weed management (IWM) strategies are a method of reducing herbicide use in agricultural practices (Swanton et al., 2010; Seyyedi et al., 2016). The CPWC is a key component of IWM programs (Knezevic et al., 2002), and identifying it is the first step in designing a successful IWM in major crops; thus, the use of the critical period threshold model will aid in crop yield improvement (Tursun et al., 2016).

The concept of CPWC can be defined as a period during the crop growing season during which weeds should be removed to prevent crop yield loss due to weed competition (Jhala et al., 2014). However, Zimdahl (1993) defined it as the time between seeding or emergence when weed competition does not reduce crop yield and the time when weed competition no longer reduces crop yield. The CPWC is regarded as an important factor in developing an alternative weed management strategy (Ahmadvand et al., 2009). It is calculated by calculating the time interval between two independently measured crop-weed competition components: the critical duration of weed interference and the critical weed-free period (Tursun et al., 2016). CPWC studies are typically conducted by keeping the crop free of weeds until a predetermined period and then allowing the weeds to emerge, or by growing weeds with the crop for a predetermined period and then removing all weeds until the end of the growing season (Ahmadvand et al., 2009).

Farmers' primary goal in their pursuit of economically efficient agricultural production is to maximize crop yield (Al-Gaadi et al., 2016). Weed-crop competition studies can provide farmers and land managers with valuable information about the best time to apply weed-control practices to protect crop yield (Swanton et al., 2015). As a result, the current study aims to investigate the effect of different weed competition periods on barley crop growth and yield under field conditions, as well as to estimate the critical period of weed control in barley. The information gathered can be used to improve weed management and increase barley crop yield.

Materials and methods

Study crop

Barley (*Hordeum vulgare* L.) is a Poaceae family annual cereal crop plant that is the fourth most important cereal crop in the world after wheat, maize, and rice, as well as the most widely distributed crop geographically (Al-Abdallat et al., 2017; Ay et al., 2018). The optimum temperature for germination of barley seeds is around 20°C, though germination can occur at temperatures as low as 3°C. Furthermore, optimal plant growth occurs in areas with 500 to 1000 mm of annual rainfall, but it can withstand drought conditions with 200 mm of annual rainfall. Barley is more resistant to saline and alkaline soils than other cereals, but it cannot tolerate impermeable, compacted soils or excessive

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humidity (Van Gaelen, 2014). The growth period of barley is about 90 to 120 days for spring varieties, and 180 to 240 days for winter varieties (El-Midany, 2020). In 2021/2022, the global average barley yield was 2.98 tons per hectare (USDA, 2022). It is grown to produce non-alcoholic beverages, as well as for animal feed and medicinal purposes (Naeem et al., 2021). Its straw can also be used to build traditional huts and grain stores (Asfaw, 2000). Because barley is a competitive crop, selecting barley cultivars with highly competitive abilities is critical for effective weed management (Watson et al., 2006). Weeds, like other cereals, compete for resources, resulting in significant yield losses (Naeem et al., 2021b). However, while barley crops can grow quickly, suppress weed pressure, and provide a high dry weight yield, they have a low protein content for forage (Houshyar, 2017).

Experimental design

A field experiment was laid out as a factorial design with the treatments arranged in a randomized complete block design with three replications, during the period from November 2017 till April 2018, in the agricultural farm at Helwan University (29° 52.11′ 66″N - 31° 18.57′ 48″E), South Cairo Governorate, Egypt. Soil preparation was conducted according to the local practices for barley production. The soil of the study site had a pH of 7.5 with loamy sand texture. The experimental factors consisted of a quantitative series of both increasing duration of weed interference and length of weed-free periods. Four cultivated plots (4 × 4 m each) were assigned for this experiment, where each plot was consisted of 9 rows spaced at 25 cm between rows, and barley grains (genotype $Giza_{126}$) were sown with a density of 270 grain m^{-2} (optimum density for barley grains production: El-Midany, 2020) (*Fig. 1*). No pre-emergence or pre-plant herbicides were used. In the first plot, nine sampling times including six initial weed-free periods: 0 (WF0), 15 (WF15), 30 (WF30), 45 (WF45), 60 (WF60) and 75 (WF75) days after crop emergence (DAE), in which the cultivated plot was kept manually free of weeds. After that, weeds were allowed to grow until harvest time (120 DAE). In the second plot, nine sampling times including six initial weed infested periods: 0 (W0), 15 (W15), 30 (W30), 45 (W45), 60 (W60) and 75(W75), in which weeds were left without removing, after that the plot was kept free of weeds until harvest. The remaining plots were used as control, where the third one was kept free of weeds, and the fourth was left without removing weeds for the period from the emergence until harvest of barley at 120 DAE. The plots were irrigated regularly according to the indigenous agricultural practices in Egypt. Barley irrigated with 200 to 300 mm water 2 to 3 irrigation during the whole cultivation. Application of nitrogen, potassium and phosphate fertilizers and pest and disease control were carried out according to the recommended agronomic practices in the region. The climate of the study area during the growing season of barley was characterized by an average temperature of 20°C and an annual rain fall of 12.7 mm (El-Midany, 2014).

Weed and crop measurements

A natural and mixed weed species population were utilized to determine the CPWC for general weed interference. Weeds began to emerge 10 days after barley planting; these weeds included *Cyperus rotundus, Bidens pillosa, Anagallis arvensis, Avena fatua, Chenopodium murale*, *Sonchus oleraceus* and *Melilotus indicus* with two other common associated species (*Medicago polymorpha* and *Euphorbia peplus*). Measurements of weed traits were exclusive to the latter two common associated weeds since both were present in significant higher cover compared to other weed species. Weed infestations

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were evaluated at the end of each treatment using three 0.5 m × 0.5 m quadrats/plot. In each quadrat, the number of barley tillers and the number of individuals of each common associated weed were counted to calculate their densities (i.e., number of individuals / unit area). Then, the whole plant individuals of barley plants and its associated weeds within each quadrat were harvested and transferred to the laboratory in polyethelene bags. In the laboratory, plant species were separated and some morphological measurements including culm (stem without sheath) diameter, root length, number of leaves, leaf length and width, sheath length, spike length and number of spikelets per each spike were measured for barley as well as shoot height for barley and its common associated weeds. The leaf area of barley plants (single sided) was measured using the equation (Kemp, 1960): $A = 0{\cdot}905\ LB$, *where* L = length of leaf; B = breadth at a point midway along the length; A = area. After the morphological measurements, the sampled shoots of barley and its associated weeds were oven-dried at 70°C till constant weight, and then the average dry weights of the shoots were calculated to estimate the aboveground biomass (DM gm^{-2}). The total biomass of all weedy species was also calculated. In addition, the grains of barley were harvested from each quadrat and weighed to calculate the yield per unit area of barley in each treatment. All measurements were carried out in three replicates.

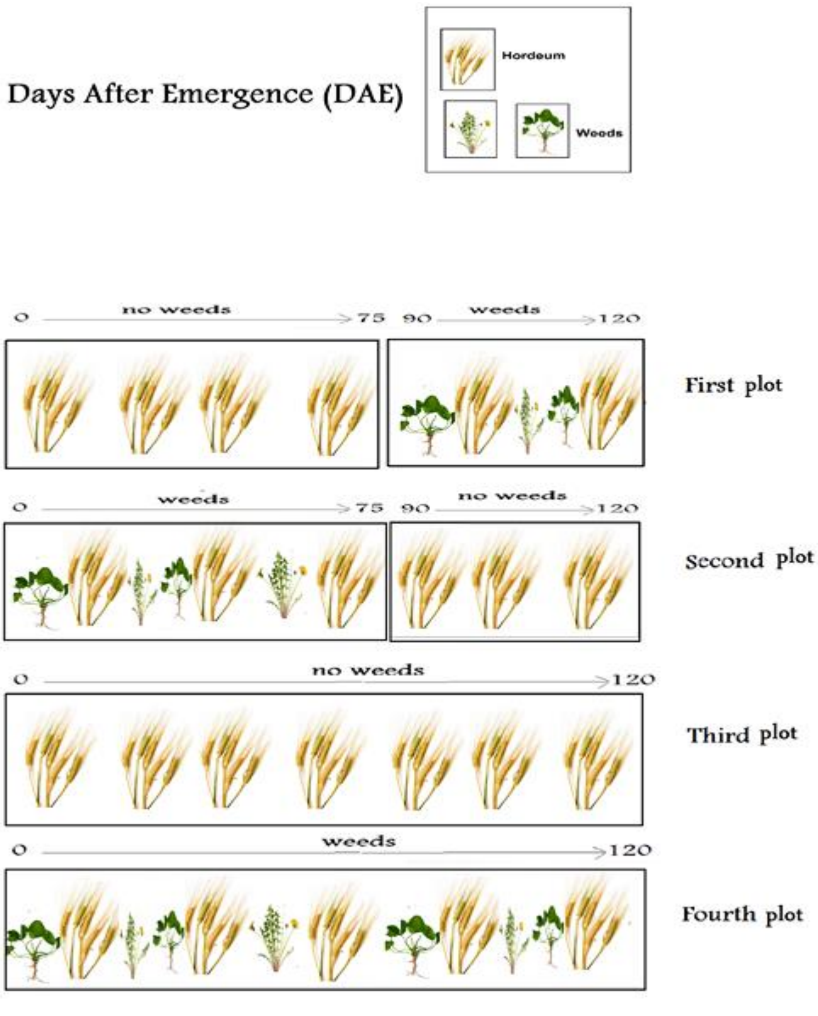

Figure 1. *Schematic diagram showing the design of the critical period of weed control experiment*

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Plant analysis

After 75 DAE, three composite plant samples were taken from the above-ground shoots (stem and leaves) of barley plants in weed-free and weed-infested plots. Samples were oven-dried before being homogenized in a metal-free plastic mill and passing through a 2 mm mesh sieve. A 1 g ground sample was digested in 20 ml of a tri-acid mixture of $H2SO_4$:$HClO_4$:HF (1:1:2 V:V:V). The Kjeldahl method was used to determine total nitrogen (N). P, Mg, Ca, K, and Na concentrations were determined using an Agilent 4210 MP-AES (Agilent, USA). These procedures were recommended by Allen (1989). The instrument settings and operational procedures were adjusted in accordance with the user manual provided by the manufacturer.

Soil analysis

At the end of the barley growing season, three composite soil samples were collected from each sampling plot's profile (0-50 cm depth). Soil samples were brought to the laboratory in plastic bags as soon as they were collected; they were air dried, passed through a 2 mm sieve to remove debris, and then packed in paper bags for mechanical and chemical analysis. Soil pH (measured with a pH meter Model 9107 BN, ORION type, Thermo Scientific, USA) and electrical conductivity were determined using 1:5 w/v soil-water extracts (conductivity meter 60 Sensor Operating Instruction Corning, USA). Bicarbonates were determined by titration against 0.01N HCl, chlorides by direct titration against silver nitrate solution with 5 percent (w/v) potassium chromate as an indicator, and sulphates by turbidimetric determination as barium sulphate at 500 nm. Phosphorus was measured with a spectrophotometer (CECIL CE 1021, Cecil Instruments Limited, Corston, UK) using molybdenum blue methods (Allen, 1989). Titration against 0.01N versenate solution with meroxide and erichrome black T as indicators yielded calcium and magnesium concentrations. A flame photometer was used to measure sodium and potassium. Allen (1989) outlines all these procedures.

Data analysis

Sigma Plot 10.0 was used to fit the curves for calculating the CPWC. The Gompertz equation was used to model the effect of weed-free period on barley grain yield during both years, while the logistic equation was used to model the effect of weed duration on yield. The Gompertz model has been shown to provide an adequate fit to yield as the length of the weed-free period increases (Hall et al., 1992; Knezevic et al., 2002). The model has the following form (*Equation 1*):

$$Y = \mathrm{A} \times \exp\{-\mathrm{B} \times \exp(-\mathrm{K} \times \mathrm{T})\} \quad \text{(Eq.1)}$$

where Y is the relative yield (measured as a percentage of the season-long weed-free period), A is the relative yield asymptote, B and K are constants, and T is the length of the weed-free period after emergence in days (DAE). Moreover, a three-parameter logistic equation was used to describe the effect of increasing duration of weeds infestation on relative yield of barley (*Equation 2*). The parameters of nonlinear regression were estimated using Sigma Plot 10.0, in line with the procedure suggested by Knezevic et al. (2002) as follow (*Equation 2*):

$$Y = ((1/(\exp(\mathrm{K} * (\mathrm{T} - \mathrm{X})) + \mathrm{F})) + ((\mathrm{F} - 1)/\mathrm{F})) * 100 \quad \text{(Eq.2)}$$

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where Y is the relative barley grain yield (% season-long weed-free control), T is the length of the weedy period after emergence in days (DAE), X is the point of inflection, and K and F are constants. The determination of the CPWC in this study was carried out based on the arbitrarily chosen yield loss levels of 5% and 10%, which was judged to be acceptable, considering the present economics of weed control (Ahmadvand et al., 2009).

Statistical analysis

Using a paired-sample t-test, the differences in soil characteristics, morphological traits, and biomass of barley between weedy and weed-free treatments were determined (SPSS, 2012).

Results

Soil properties

The soil of the cultivated barley in the experimental farm of Helwan University showed no significant differences in the investigated variables, except soil pH and K, between weedy and weed-free cultivated plots (*Table 1*). The soils of the weedy and weed-free plots were alkaline (pH: 7.20 and 7.75) with high salinity (8.61 and 8.56 µs cm^{-1}), respectively. The nutrients of the soil were characterized by high content of K, followed by Ca, Mg and P.

Table 1. *Soil characteristics (mean ± standard deviation) of the weedy and weed-free cultivated plots of barley in the experimental farms of Helwan University*

Soil variable		**Sampling plot**		**T-value**
		Weedy	**Weed-free**	
pH		7.20±1.02	7.75±0.89	2.47*
EC (µs cm^{-1})		8.61±0.93	8.54±0.90	1.23
Cl^-	**(mg kg^{-1})**	2.64±0.62	2.72±0.44	0.98
HCO_3^-		2.66±0.12	2.70±1.01	1.06
SO_4^{2-}		1.75±0.09	1.54±0.84	2.10
P		44.60±8.35	45.49±6.34	1.34
K		290.08±38.76	229.50±27.64	2.53*
Ca		62.00±13.42	66.00±11.23	1.86
Mg		50.00±14.63	57.20±8.46	1.04
Na		3.82±1.02	4.48±1.06	0.98

*Significance at $p < 0.05$

Growth measurements

The growth measurements of barley in the experiment indicated the significant impact of weed interference on the growth properties of barley plants (*Table 2*). It was found that the growth measurements of barley in the weed-free periods were higher than those in the weed-infested periods. In the weedy plot, some growth criteria were significantly ($P < 0.05$) increased from the weed infestation to the weed-free period. For example, crop plant density (467.5 to 772.7 tillers m^{-2}), shoot length (46.6 to 71.1 cm), sheath length (6.4 to 6.9 cm), leaf area (13.7 to 18.2 cm^2) and the plant biomass (256.5 to 627.1 g DM

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m^{-2}). In the same context, the plots that start without weed infestation showed slight increase in the growth parameters of the barley plants. Whereas, the plant density was significantly increased from 605.5 to 731.3 tillers m^{-2}, while the shoot length ranged between 45.7 and 72.9 cm, the sheath length between 6.5 and 9.5 cm, and the plant biomass had a range from 224.3 to 551.5 DM gm^{-2}, before and after change weed presence, respectively.

Table 2. *Growth characteristics (mean ± standard deviation) of barley plants in weedy and weed-free plots before and after change from weedy to weed free and vice versa*

Parameters	**Weedy plots**			**Weed-free plots**		
	Before change	**After change**	**T-test**	**Before change**	**After change**	**T-test**
No. of tillers m^{-2}	467.5±241.8	772.7±55.0	4.2**	605.5±228.4	731.3±194.3	3.3*
Shoot length (cm)	46.6±19.6	71.1±4.7	6.2**	45.7±15.4	72.9±9.9	15.0***
Culm diameter (cm)	0.3±0.1	0.3±0.1	1.3	0.4±0.5	0.3±0.1	0.7
Root length (cm)	6.0±2.2	7.6±2.1	1.2	5.5±3.0	6.6±1.5	0.6
No. of leaves/individual	4.3±1.0	4.7±0.5	0.8	4.1±1.0	3.7±0.4	1.1
Leaf length (cm)	18.9±4.4	20.1±2.0	0.4	18.6±4.0	17.9±3.5	1.3
Sheath length (cm)	6.4±1.8	9.6±1.6	4.2**	6.5±1.3	9.2±0.8	8.4***
Leaf width (cm)	0.8±0.3	1.0±0.3	1.1	0.7±0.2	0.7±0.2	1.2
Leaf area (cm^2)	13.7±1.2	18.2±3.6	2.4*	11.8±1.3	11.3±1.7	1.1
Shoot biomass (g DM m^{-2})	248.0±82.2	622.3±102.4	7.4**	218.5±77.2	540.8±123.4	8.8***
Root biomass (g DM m^{-2})	8.5±2.8	4.7±1.5	1.6	5.9±4.7	10.7±3.2	2.2
Total biomass (g DM m^{-2})	256.5.±66.1	627.1±102.3	7.2**	224.3±75.6	551.5±125.4	9.0***

*: $p < 0.05$, **: $p < 0.01$, ***: $p < 0.001$

Impact of weed infestation on the functional traits of barley

Shoot length

The shoot length of barley and its common associated weeds indicated that the barley plant continues to increase in height until reach its maximum (72.9 cm) at the end of weed infestation period (75 DAE), while *Medicago polymorpha* reached its maximum height (19.7 cm) after 60 DAE, and then decreased to 18.0 cm at the end of the weedy period (*Fig. 2*). In addition, the maximum height of *Euphorbia peplus* (7 cm) was recorded after 75 DAE. These results indicated that *M. polymorpha* was affected by the highly competitive effectiveness more than *E. peplus*.

Plant density

The impact of weeds infestation on the plant density showed that the average plant density (599.5 tillers m^{-2}) in the weed-free plot was significantly higher than 497.5 tillers m^{-2} in the weed-infested plots with a reduction percentage of 17.0% (*Table 3*). In the weed-free plot, the plant density increased with increasing the time till reaches its maximum (824.0 tillers m^{-2}) after 90 DAE, and then decreased to reach its minimum (344.0 tillers m^{-2}) at the harvest time (120 DAE) due to weed infestation. On the other hand, the barley in the weedy plot showed slight increase in density until reaches its maximum (644.0 tillers m^{-2}) after 75 DAE, and then gradually decreases to reach

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240.0 tillers m^{-2} at the harvest time. It is worth to note that the highest reduction percentage (32.0%) was observed after 90 DAE, while the lowest value (5.0%) was recorded after 105 DAE.

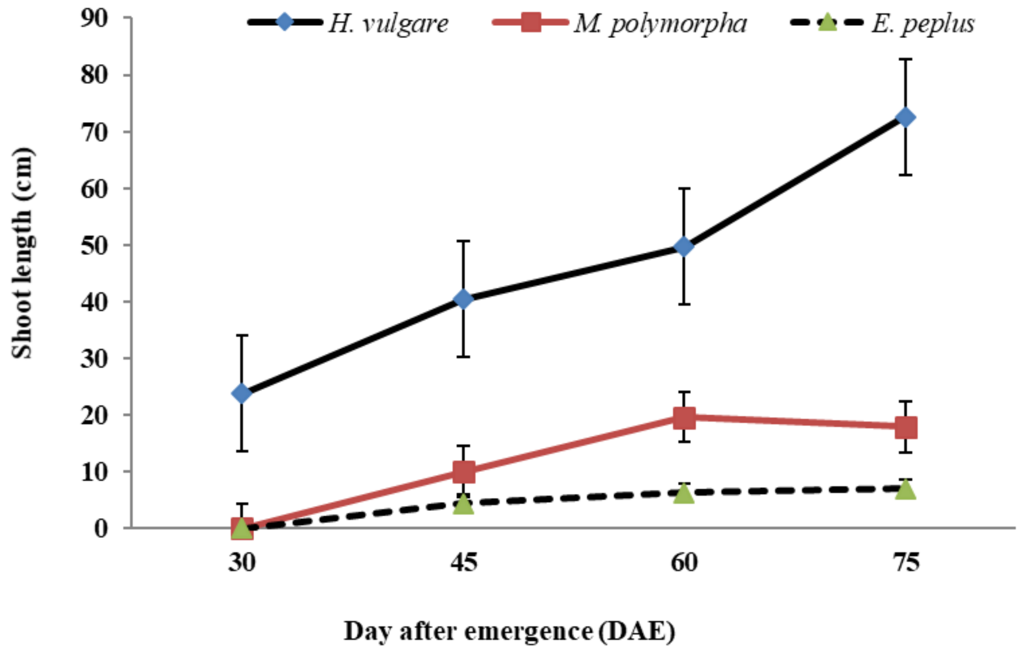

Figure 2. *Shoot length (cm) of barley and its common associated species in the weed-infested plots. H. vulgare: Hordeum vulgare, M. polymorpha: Medicago polymorpha, E. peplus: Euphorbia peplus. Vertical bars are the standard errors*

Table 3. *Plant density (tillers m^{-2}) of barley grown in weedy and weed-free plots, and the calculated reduction % in barely density in weedy plots compared to the weed-free plots*

Days after emergence (DAE)	**Plant density (tillers m^{-2})**		
	Weed-free plot	**Weedy plot**	**Reduction (%)**
15	528	424	20
30	560	456	19
45	568	496	13
60	712	588	17
75	656	644	2
90	824	560	32
105	604	572	5
120	344	240	30
Mean ± standard deviation	599.5± 140	497.5± 126	17± 8
T-test	3.8**		

The barley plants had a high competitiveness compared with its common associated weeds including *M. polymorpha* and *E. peplus* (*Fig. 3*). The plant density curve of barley plants in presence of the two common weeds was sigmoid, where it was gradually increased till 30 DAE, and then showed sharp increase until it reached its maximum

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(652.0 tillers m^{-2}) after 60 DAE and after that it exhibited slight increase until reached 666.0 tillers m^{-2} at the end of weed infestation period (75 DAE). However, *M. polymorpha* and *E. peplus* started to emerge after 45 DAE with density of 4.0 and 10.0 individuals m^{-2}, respectively, and then reached their maximum (12.0 and 20.0 individuals m^{-2}) after 60 DAE corresponding to the maximum barley density, which then started to increase gradually in response to declining weed density.

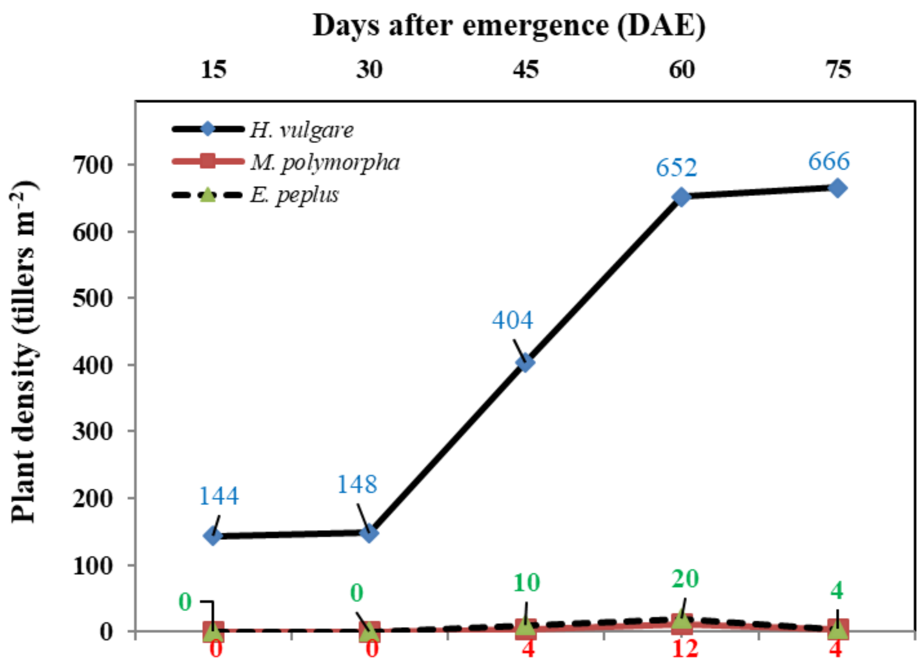

Figure 3. *Plant density of barley (tillers m^{-2}) and its common associated species (individuals m^{-2}). H. vulgare: Hordeum vulgare, M. polymorpha: Medicago polymorpha, E. peplus: Euphorbia peplus. Vertical bars are the standard errors*

Plant biomass

The data of shoot and total biomass of barley plant and its common associated weeds showed great competitive potential of barley compared to the other weeds (*Fig. 4*). The aboveground biomass of barley showed gradual increase until reached 83.0 g DM m^{-2} after 45 DAE, and then showed exponential increase to 539.4 g DM m^{-2} at the end of the weed infestation period. Meanwhile, the biomass of *M. polymorpha* and *E. peplus* had its maximum (14.8 and 15.4 g DM m^{-2}, respectively) after 45 DAE, and then started to decrease by increasing the biomass of barley, Comparing the average total biomass, including above- and below-ground parts, of barley with that of all associated weeds in the weed-infested plots showed that the biomass of both barley and associated weeds gradually increased until 45 DAE (*Fig. 5*). After that the biomass of barley continued to increase, while the biomass of weeds declined and then increased at the end of infestation period.

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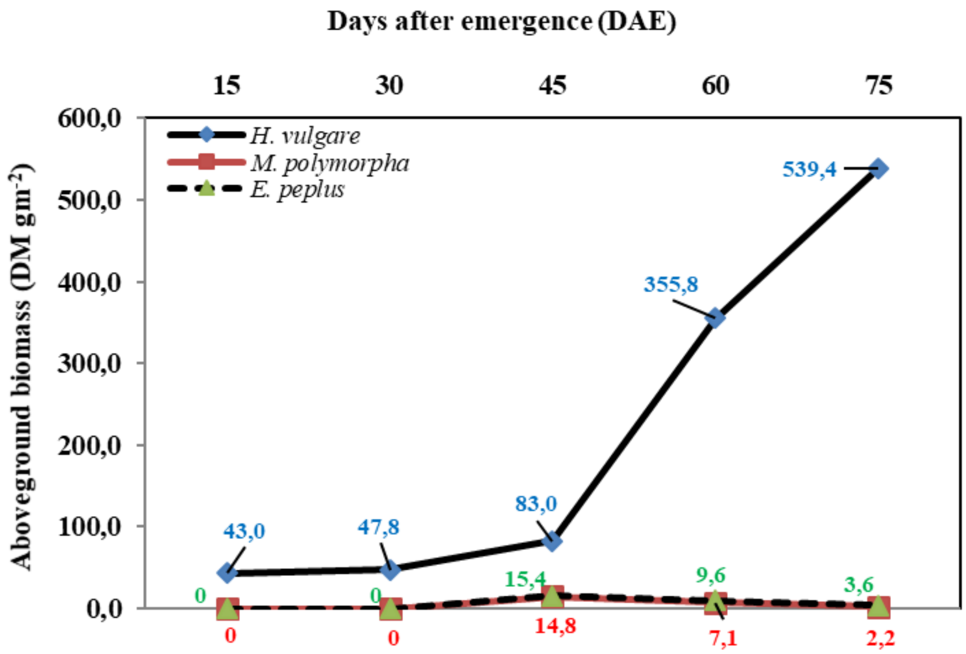

Figure 4. *Aboveground biomass (g DM m^{-2}) of barley and its common associated species. H. vulgare: Hordeum vulgare, M. polymorpha: Medicago polymorpha, E. peplus: Euphorbia peplus*

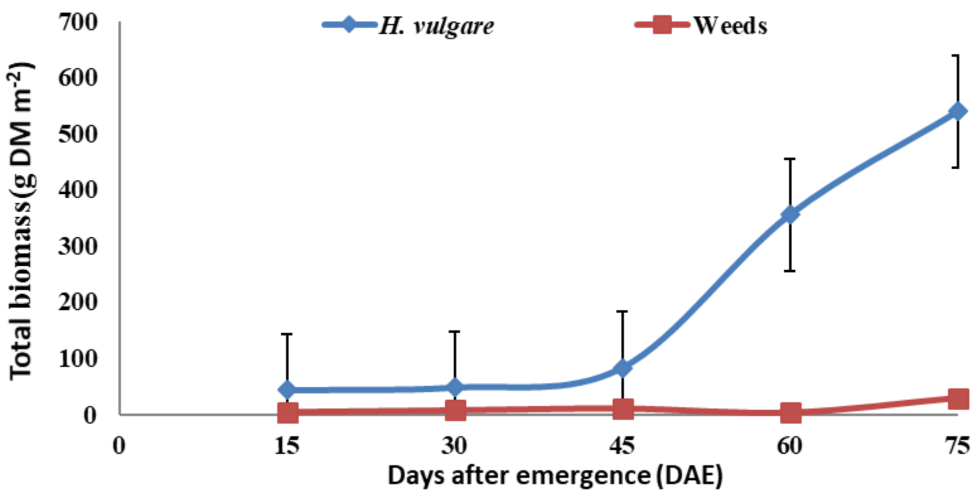

Figure 5. *Total biomass (g DM m^{-2}) of barley and all recorded associated weed species in the experimental farm at Helwan University. Vertical bars are the standard errors*

Plant nutrients

The nutrients content of the barley shoots indicated significant differences ($P < 0.05$) for all nutrients (except P and K) between weed-infested and weed-free plants (*Table 4*). It was found that the total N, Ca, Mg and Na contents (1.87, 0.16, 0.41 and 0.58%) of barley from weed-free plot were significantly higher than that recorded for plants from weed-infested plot (1.79, 0.12, 0.31 and 0.43%, respectively). On the other hand, the

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contents of most nutrients (except P and Na) of the barley grains from weed-free plots were significantly higher than those of the grains collected from weed-infested barley.

Table 4. *Impact of weed interference on nutrients concentration (mean ± standard deviation) of the shoots and grains of barley cultivated in weed-infested and weed-free plots*

Nutrient (%)	Shoot			Grains		
	Weedy	**Weed-Free**	**T-test**	**Weedy**	**Weed-Free**	**T-test**
N	1.79±0.10	1.87±0.15	2.4*	1.31±0.26	1.58±0.22	2.4*
P	0.16±0.02	0.13±0.02	2.6*	0.43±0.01	0.40±0.03	0.35
K	1.35±0.17	1.39±0.19	1.34	1.20±0.16	1.53±0.19	7.8**
Ca	0.12±0.01	0.16±0.06	3.1*	0.05±0.02	1.08±0.06	44.3***
Mg	0.31±0.05	0.41±0.07	3.4*	0.29±0.18	0.36±0.02	7.6**
Na	0.43±0.24	0.58±0.27	4.1*	0.04±0.01	0.04±0.02	0.5

Yield responses to weed control

The present study recorded that the beginning of CPWC based on 10% yield loss occurred at 63 DAE, while the end of CPWC occurred at 79 DAE (*Fig. 6*). According to 5% yield loss, the beginning of the CPWC occurred by 41 DAE, while the end occurred by 102 DAE. The onset of the CPWC became earlier and it ended later as the predetermined acceptable yield loss level decreased from 10% to 5%. Moreover, it was found that in the weed free plots the barley yield increased with duration until it reached its maximum value (3.2 t ha^{-1}) by 90 DAE, and then decreased gradually under weed infestation (*Table 5*). On the other side, the barley yield of the weed-infested plot had its maximum value (2.2 t ha^{-1}) after 75 DAE, and then fluctuated by removing weeds.

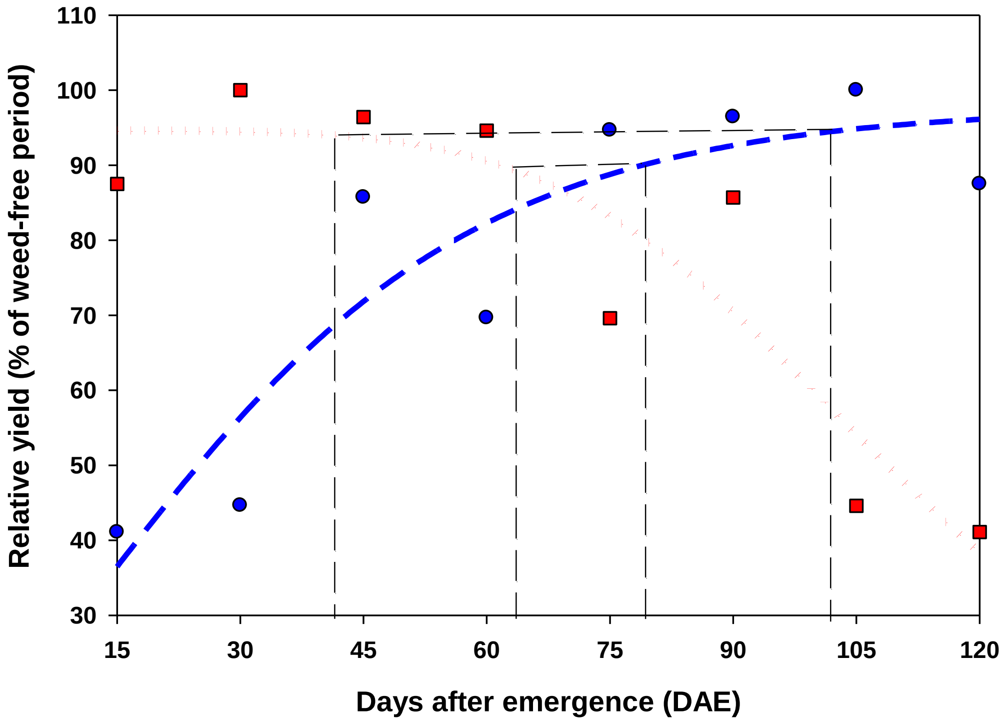

Figure 6. *Effects of increasing duration of weed interference (squares) and weed-free periods (circles) from crop planting on barley yield*

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***Table 5.** Impact of weeds on the yield (t ha^{-1}) of barley crop cultivated in weed-free and weedy plots*

Days after emergence (DAE)	Plant yield (t ha^{-1})		
	Weed-free plot	Weedy plot	Reduction (%)
15	2.0	1.5	25.0
30	2.2	1.6	27.3
45	2.2	1.8	18.2
60	2.7	2.1	22.2
75	2.5	2.3	8.0
90	3.2	2.0	37.5
105	2.3	2.0	13.0
120	1.3	0.9	30.8
Mean ± standard deviation	2.3± 0.5	1.8 ± 0.5	22.8 ± 8.5
T-test	5.2***		

Discussion

In recent years, the areas occupied by barley have decreased due to a variety of economic, climatic, and other factors, and thus maintaining high yields requires optimizing all processes in cultivation technology and taking climate change into account (Georgiev and Delchev, 2016). Furthermore, if weed species are not adequately controlled, it can result in significant economic losses (Soltani et al., 2014). The experimental barley fields in the current study had a low weed abundance, which could be attributed to its reported allelopathic activity (Schuster et al., 2020). The measured morphological parameters of barley plants were found to be higher in non-weedy barley fields than in weedy barley fields. Non-weedy barley plants had higher shoot heights than weedy plants. *M. polymorpha* and *E. peplus* reached their maximum heights after 60 and 75 DAE, respectively, and then decreased to the minimum at the end of the weedy period, whereas barley plants continued to grow until reaching their maximum at the end of the weedy period (75 DAE). These findings indicated that *M. polymorpha* was more influenced by barley's highly competitive effectiveness than *E. peplus*. Belete et al. (2018) attributed the increased plant height in the weedy plot to intense competition among plants, which causes them to elongate in search of light and lack abundant growth, allowing the plants to grow taller. Furthermore, Vandeleur and Gill (2004) reported that taller barley cultivars were typically better weed tolerators and suppressors of weed growth. Similar findings have been reported for rice plants, where their height is significantly reduced when rice competes with weeds for 70 days or longer, and rice plant height is inversely proportional to weed competition length (Micheal et al., 2013).

The current study observed that barley growth measurements in weed-free periods were higher than those in weed-infested periods, with the leaf area increasing significantly ($P < 0.05$) from the weed infestation to the weed-free period. According to Chowdhury et al. (2015), weed competition for growth factors with crop plants was absent or negligible in weed-free crops, resulting in increased shoot length. Furthermore, the decrease in barley leaf dimensions with increased weeds was caused by increased weed biomass or weed competition with crop, which may have reduced the availability of environmental resources to crop plants, and hampered crop canopy establishment (Zafar

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et al., 2010). Therefore, removal of weeds at early crop growth stages helped plants to make full use of growth factors without facing any competition effect.

Weed density appears to be important in determining when the CPWC begins (Kumar et al., 2020). In the weedy plot, barley density increased gradually until it reached its maximum after 75 DAE, then decreased gradually until it reached its minimum at harvest time. However, in the presence of the two common weeds, the plant density curve of barley plants was sigmoid, with a gradual increase until 30 DAE, then a sharp increase until it reached its maximum after 60 DAE, and then a slight increase until the end of the weed infestation period (75 DAE). *M. polymorpha* and *E. peplus* appear after 45 DAE, reach a peak after 60 DAE, and then decline sharply. According to Swanton et al. (2015), after weed emergence time, weed density is the second most important variable, as there is clearly a relationship between weed density and duration of interference. They hypothesized that weeds that emerge with or before the crop are by far the most competitive and cause the most yield loss, whereas weeds that emerge later than the crop are much less competitive in terms of crop yield loss. Furthermore, Bagheri et al. (2020) attributed this trend of weed density suppression to an increase in barley plants' competition ability against weeds at higher crop density. When compared to its common associated weeds, such as *M. polymorpha* and *E. peplus*, barley plants had a high competitiveness. It was discovered that having a larger number of tillers increases the crop stand's shading ability (Hoad et al., 2006). Seavers and Wright (1999) demonstrated this in a study of wheat, barley, and oat cultivars, where cultivars with greater tiller economy had a superior suppressive ability against weeds due to a cultivar's ability to maintain high levels of light interception.

Crop variety, sowing rate, weed species and density, and crop emergence time relative to the weed can all influence weed competition (El-Midany, 2020). With a reduction percentage of 17.0 percent, the average barley density in the weed-free plot was higher than that in the weed-infested plot until harvest. This result agreed with Singh et al. (2017), who found that weed-free treatments had the highest number of effective tillers, while weedy check treatments had a significantly lower number due to higher weed density and biomass. Furthermore, Chowdhury et al. (2015) reported that the low number of tillers in the weedy plot was due to increased competition between crop plants and weeds for nutrients, air space, light, and water. According to Belete et al. (2018), the production of more total tillers in weed-free plots may be attributed to better access to space, nutrients, water, and light, which allowed plants to produce more tillers m^{-2}, whereas the reduction in tiller number m^{-2} may be due to increased weed population and continuous competition reduced access to different resources.

The biomass of barley plants and their associated weeds increased gradually until 45 DAE, when the biomass of barley continued to increase while that of weeds declined and then increased again at the end of the infestation period. Micheal et al. (2013) discovered that the lowest weed dry weight was recorded in plots that were weed-free for more than 45 days during the rice crop season. Hugo et al. (2014) discovered that the highest biomass of naked crabgrass (*Digitaria nuda*) was recorded at 78 DAE, which corresponded with corn plant tasseling. According to Kumar et al. (2020) and Mondani et al. (2011), weed biomass increased with increasing weed infestation duration and decreased with increasing weed free period duration. Furthermore, weed control after 20 DAE reduces weed density and dry weight by up to 76 and 95%, respectively, and increases grain yield by up to 34% (Ali et al., 2014).

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Crops and weeds' competitive ability for nutrient uptake in agricultural ecosystems will be primarily determined by their intrinsic nutrient requirements and uptake efficiencies (Swanton et al., 2015). The total N, Ca, Mg, and Na contents of barley shoots from weed-free plot were significantly higher than those found in weed-infested plot plants. Furthermore, the contents of most nutrients (except P and Na) in barley grains from weed-free plots were significantly higher than those in weed-infested barley grains. The lower nutrients contents of barley in the weedy plots may be due to the high accumulation potential of the associated weeds to these nutrients (Galal and Shehata, 2015).

The barley yield increased with duration in the weed-free plot until it reached its maximum value (3.2 t ha^{-1}) by 90 DAE, and then decreased gradually under weed infestation. The weed-infested plot's barley yield, on the other hand, peaked at (2.2 t ha^{-1}) after 75 DAE and then fluctuated as weeds were removed. According to Belete et al. (2018), the maximum weed control enhanced the production of effective tillers, which subsequently contributed towards the increase in wheat yield. In addition, Singh et al. (2017) reported that the presence of weeds throughout the growing season resulted in a 24 percent reduction in grain yield when compared to weed-free conditions. At harvest, the yield of barley in the weed-free plot was higher than the yield of barley in the weed-infested plot. Singh et al. (2017) discovered similar results in a barley crop. According to Walters and Craig (2017), a significant part of the effect of weed competition on barley yield was due to a decrease in the number of grain-bearing ears per plant, which affected yield. Furthermore, weeds can reduce barley yield, so integrated weed management practices should be used to control weeds in barley crops (GRDC, 2016). Weeds were discovered to reduce yields, lower crop market value by reducing quality, and raise harvesting, drying, and cleaning costs (Galal and Shehata, 2015).

In the current study, the biomass of *M. polymorpha* and *E. peplus* peaked at 45 DAE and then began to decline as the biomass and density of the barley plant increased. This result was consistent with the findings of Dhima and Eleftherohorinos (2001), who found that increasing crop density resulted in a significant reduction in weed biomass. In a similar study, Belete et al. (2018) attributed the higher wheat grain yield to lower weed dry weight and efficient resource utilization, while the lower yield was attributed to weed infestation, accumulation of high dry matter in weeds, and the presence of different weed species in weedy plots. Similar results were reported by Ud Din et al. (2016) for maize and Latif et al. (2021) for broccoli, and Simarmata et al. (2018) for sweet corn.

Knowing the critical periods for weed control helps growers decide whether to pursue additional weed control measures to protect crop yield (Swanton et al., 2015). To determine the predicted and observed barley yield as affected by the duration of the weed-infested or weed-free periods, the Gompertz and logistic equations were used. According to the current study, the start of CPWC based on a 10% yield loss occurred at 63 DAE, and the end of CPWC occurred at 79 DAE. However, based on a 5% yield loss, the start of the CPWC occurred 41 DAE earlier, while the end occurred 102 DAE later. Bukun (2004) discovered that weeds must be controlled from 15 to 84 DAE for efficient yield in a similar study on Turkish cotton, whereas Mondani et al. (2011) and Baziramakenga and Leroux (1994) recorded CPWC of 20–60 DAE and 15–68 DAE, respectively, for the minimum potato yield loss. Furthermore, when yield losses exceeded 5%, the CPWC of corn production ranged between 12 and 44 DAE (Hugo et al., 2014), while acceptable yield loss levels of 5% and 10% were 20 and 9 days (Ghanizadeh et al.,

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2009) and 48 and 35 days, respectively (Tursun et al., 2016). Furthermore, the estimated CPWC for a 10% acceptable rice yield loss was 17–53 DAE (Micheal et al., 2013).

Conclusion

According to the current study, the start of CPWC based on a 10% yield loss occurred at 63 DAE, and the end of CPWC occurred at 78 DAE. However, based on a 5% yield loss, the start of the CPWC occurred 41 DAE earlier, while the end occurred 102 DAE later. As a result, weed removal at the CPWC is urgently needed to assist plants in making full use of growth factors without competition, resulting in crop yield loss. Non-weedy barley fields had higher measured morphological parameters of barley plants, such as plant height and leaf area, than weedy barley fields. The average barley density and biomass, as well as the inorganic nutrient content, were higher in the weed-free plots than in the weed-infested plots. Finally, the current study concluded that barley plants were highly competitive when compared to their commonly associated weed species.

Competing interests. The authors declare that they have no competing interests.

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