Eco-Biological Studies on Wild Sunflower (*Verbesina encelioides*) in the Central Rift Valley of Ethiopia

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Abstract

Wild sunflower threatens crop production, animal husbandry, and biodiversity in areas where it has spread. Even though the weed has already concurred huge areas of different land use systems of the Central Rift Valley, there is no available information on its eco-biology. Thus, this study was conducted to generate eco-biological information on wild sunflower by investigating the effects of different seasons of the year, soil ploughing, seed storage time, and burial depth on seed germination and seedling emergence. Wild sunflower matured in about 128 to 141 days, during which it attained a height of up to 82 cm. The weed could produce up to 22 branches and 32 flower heads per plant. The weed attained a biomass yield of about 26 and 34 g plant^{-1} at Adamitulu and 35 and 44 g plant^{-1} at Melkassa at flowering and maturity, respectively. Wild sunflower produced 813 to 1124 seeds per plant. Seedling emergence m^{-2} averaged 42.6 at Melkassa and 34.4 at Adamitulu under unploughed soil but declined to 23.8 and 20.6, respectively, when the plot was ploughed. During the summer, the highest seedling densities of 38.3 and 54.7 plant m^{-2} emerged at Adamitulu and Melkassa, respectively. The proportion of germinating seeds was highest in seeds stored for 24 weeks (97%), and emergence increased with increasing storage time until germination stabilized while only 2% germinated from freshly harvested seeds. The required storage time for 50% germination was only 2.8 weeks. The percentage of seedling emergence was highest for seeds placed on the soil surface (94%), and decreased with the burial depth; no seedlings emerged from a depth of 6 cm. It was observed that a burial depth of only 2.7 cm reduced seedling emergence by 50%. Overall, the information generated on the biology and ecology of wild sunflower in this study will assist in the development of its management strategies.

Keywords: Seed burial depth, weed seed germination, storage time, weed emergence

Introduction

Wild sunflower (*Verbesina encelioides)*, an exotic weed native to Mexico and the United States has become widely distributed in many parts of the world (Feenstra and Clements, 2008; Jain *et al*., 2008). Currently, it is being widely spread in

Ethiopia in crop and non-crop fields after a rare occurrence reported in eastern Ethiopia in 1998 (Witt and Luke, 2017; Amare *et al*., 2022). The plant is an erect annual herb resembling the sunflower, ranging in height from 0.3 to 1.6 m (Feenstra and Clements, 2008; Witt and Luke, 2017; Goyal *et al*., 2019). The plant is self- and cross-pollinated and reproduces by seed (EPPO, 2012). According to Taleb *et al*. (2011), wild sunflower completes its life cycle in 80 days, and its seeds can germinate within a temperature range of 8 °C to 35 °C, with the optimum range being 15 °C to 25 °C.

Wild sunflower is a competitive weed that invades a variety of habitats, including crop fields, fallow lands, grazing lands, residential areas, and roadsides (Brunel *et al*., 2010; Taleb *et al*., 2011; Mohammad, 2014; Goyal *et al*., 2019; Amare *et al*., 2022). It threatens native plants and causes biodiversity reduction (Sade *et al*., 2007; Mohammad, 2014). The weed also competes with its neighbors via allelopathic interference; for instance, it is more aggressive than co-occurring species like *Amaranthus viridis* and *Senna occidentalis* (Mehal *et al*., 2022). The highest density of wild sunflower was also observed to significantly reduce the diversity of other plant communities (Amare *et al*., 2022). On common bean fields of the Central Rift Valley (CRV) of Ethiopia, a yield loss as high as 88.1% has been observed with sunflower density of 24 plants m^{-2} (Amare *et al.* unpublished data). Farris and Murray (2006) reported a 50% yield loss on peanut with wild sunflower density of 3.2 plants m^{-1}.

A good understanding of weed biology and ecology is key to making management decisions and developing integrated weed management strategies. Weed seed germination and seedling emergence are influenced by various factors, including soil ploughing conditions, seasons of the year, seed storage time, and seed burial depth (Huarte *et al*., 2016; Lozano *et al*., 2018; Zhao *et al*., 2018; Cabrera *et al*., 2020). The soil disturbance in conventional tillage systems could increase weed seed emergence (Ebrahimi and Eslami, 2012), probably by altering the burial depth. Environmental factors, such as light, can explain the stimulating effect of tillage on weed seedling emergence (Cabrera *et al*., 2020). Besides, many weed seeds that require light for germination usually emerge when they are close to the soil surface (Adkins *et al*., 2002). For wild sunflower, cultural practices such as no-till and minimum tillage may promote greater seedling emergence (Goyal *et al*., 2019). Concerning seasons, Javaid *et al*. (2010) observed that parthenium seeds exhibit variable dormancy and germination percentages at different seasons of the year.

Fresh weed seeds are mostly known to have a high level of dormancy (Chauhan, 2022) and it was reported that increasing the seed storage time increases seed germination in some weed species (Wang *et al*., 2010; Lozano *et al*., 2018).Seedling emergence is also influenced by seed burial depth, which influences the availability of stored reserves, light, moisture, and temperature (Shoab *et* *al*., 2012). There are, however, contrasting results regarding the effect of seed burial depth on wild sunflower. There was no seedling emerging beyond 2.5 cm depth (Al-Farraj *et al*., 1988); whereas, Goyal *et al*. (2019) reported that seeds of wild sunflower can be planted up to 4 cm deep in soil and allowed to develop. This implies that more research is needed to prove how varied soil burial depths affect wild sunflower seedling emergence.

Evidence on weed biology and ecology, along with environmental factors affecting weed seed germination and seedling emergence, helps in the development of an integrated weed management program. Furthermore, it assists in understanding the invasion potential of weed species. However, there is a paucity of information on the eco-biology of wild sunflower in Ethiopia. Therefore, this study was conducted to generate eco-biological information on wild sunflower by investigating the effects of different seasons of the year, soil ploughing, seed storage time, and burial depth on seed germination and seedling emergence of wild sunflower in the CRV of Ethiopia.

Material and Methods

Description of the study areas

Experiments were conducted at Melkassa and Adamitulu sites in the CRV of Ethiopia during 2021 and 2022. Melkassa is located at 8.42ºN latitude and 39.33ºE longitude with an altitude of 1553 meters above sea level, while Adamitulu is located at 7.86ºN latitude and 38.71ºE longitude with an altitude of 1690 meters above sea level. There are four distinct seasons in Ethiopia: autumn (September to November), winter (December to February), spring (March to May), and summer (June to August). The areas receive the highest rainfall during the summer season, with peaks occurring in July and August (Fig. 1). The soil of the experimental sites is generally loam or sandy loam in texture with a pH of 6.8–7.6, an average N of 0.04%–0.12%, available phosphorus of 16.88 to 17.14 ppm, and an organic carbon content of 0.8%–1.7%.

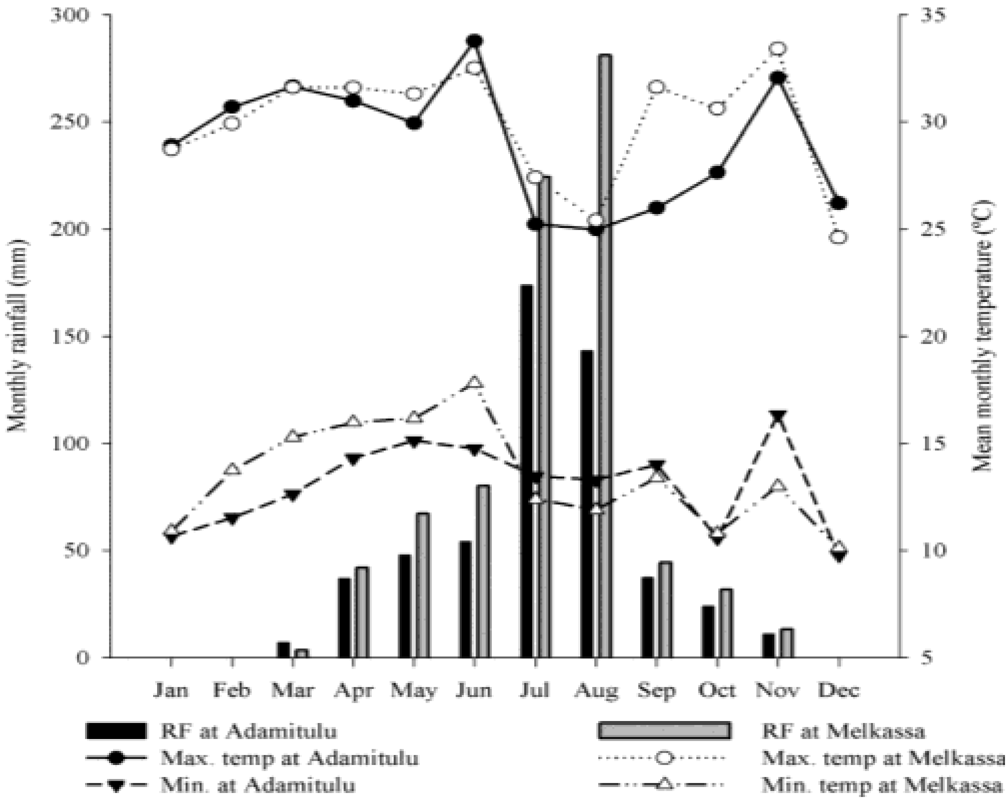

Figure 1. Monthly rainfall and mean monthly maximum and minimum temperature at Adamitulu and Melkassa (Max, maximum; Min, minimum; RF, rainfall; Temp, temperature).

Experimental procedures

Seedling emergence in relation to ploughing and seasons

The effect of seasons and soil ploughing on seedling emergence was determined in an open field from January 1, 2021 to December 31, 2021 at two locations, Adamitulu and Melkassa, where wild sunflower is well established. The experiment was set up in a randomized complete block design with five treatments in four replications. Fields with wild sunflower were selected, cleaned, marked out and divided into five plots (3 m by 2 m). Four seasons of the year were considered as treatments i.e., autumn, winter, spring and summer. Each plot was manually dug by a hoe at a depth of 2-4 cm during the first month of each season while one plot was left undisturbed (control treatment) throughout the seasons. A permanent subplot of 1 m × 1 m was established in the center of each plot and all emerged seedlings within it were counted and removed every 15 days throughout the study period to determine seedling emergence in relation to season and ploughing. To determine the phenological growth stages of wild sunflower, the main production season that starts in June was selected. Here, five emerged plants in the un-ploughed plot were tagged at seedling emergence and followed.

Data were collected on days to reach the different growth stages (seedling, vegetative, bud formation, flowering, and maturity), plant height, number of branches per plant, number of flower head per plant, number of seeds per plant and biomass at each growth stages.

Effect of seed storage time on seed germination

Seeds were collected from the main stem of wild sunflower starting from September 2021 up to June 2022 from Melkassa area. The seeds were sun-dried and kept in storage until the experiment started. The seeds were stored in a paper bag at room temperature, and the germination bioassays were carried out in July 2022 at the Plant Protection Laboratory of Melkassa Agricultural Research Centre (MARC).

The experiment was set up in a randomized complete design having eight treatments in six replications. The treatments were eight storage times, i.e., freshly harvested seeds and seeds stored for 2, 4, 8, 16, 24, 32, and 40 weeks after harvest. The germination of wild sunflower seeds was assessed in a laboratory by placing 60 seeds on two layers of filter paper (Whatman No. 1) in a 9-cm-diameter Petri dish. Germination was considered successful when the radicle broke through the seed coat (Chauhan and Johnson, 2008). Germinated seeds were counted daily for 15 days (from the beginning of the experiment to the time germination stabilized). The germination values were defined as the ratio of the number of germinated seeds to the total number of seeds per Petri dish.

Effect of seed burial depth on seedling emergence

A pot experiment was conducted in a lath house to investigate the effect of burial depth on the emergence of wild sunflower seeds. The soil used for this experiment (clay 16%, silt 29%, and sand 55%; pH 6.85; organic carbon 1.65%; available P 17.28%; and total N 0.12%) was collected from where the seeds for the experiment were collected and then sterilized to kill any viable seeds. The treatments (eight burial depths) were arranged in a completely randomized design with four replications. In each plastic pot measuring 10 cm in height and 12 cm in diameter, 30 seeds were placed evenly on the soil surface (0 cm) and covered with the same soil to achieve the desired depths, i.e., 1, 2, 2.5, 3.5, 4.5, 5, and 6 cm. Pots were watered regularly to maintain adequate soil moisture. The seedlings were considered emerged when the coleoptile was visible above the soil surface. Emergence was counted daily for 22 days until further emergence was not observed for about a week. At the end of the experiment, soil from the pots with no plant emergence was sieved to identify whether the coleoptile failed to reach the soil surface or the seeds failed to germinate (Yue *et al*., 2021), as any ungerminated seeds were tested for viability in a Petri dish (Vila *et al*., 2005).

Statistical analysis

The seedling emergence experiment data were subjected to an analysis of variance using the R program version 4.0.5, and the homogeneity of variance was assessed using the F-test as described by Gomez and Gomez (1984). Since no seedlings emerged during the dry season (winter), it was not included in the data analysis. Two sample t-tests were computed for the phenological stages, growth, and seed production studies. Regression analysis was used for the seed burial depth and seed storage time experiments. To fit variation trends in seed germination and seedling emergence percentages (%) obtained at different storage times and burial depths, a three-parameter sigmoid model generated by Sigma Plot was used (Chauhan and Johnson, 2008 and 2011; Yue *et al*., 2021). The fitted models were:

$$G(\%) = G\,max/(1 + \exp(-(x - T50)/G\,rate))\ldots\ldots\ldots\ldots\ldots 1;$$

Where G (%) is the total germination percentage (%) at storage time x, G_{max} is the maximum germination percentage (%), T50 is the time to reach 50% of maximum seed, and G_{rate} is the slope of the curve.

$$G(\%) = G\,max/(1 + \exp(-(x - x50)/G\,rate))\ldots\ldots\ldots\ldots\ldots 2$$

Where G (%) is the total germination percentage (%) at time x, G_{max} is the maximum germination percentage (%), x50 is the storage time at which 50% of seed germination is achieved, and G_{rate} represents the slope.

$$E(\%) = Emax/\,(1 + exp\,(-(x - x50)/b))\ldots\ldots\ldots\ldots\ldots 3;$$

Where E (%) is the cumulative seedling emergence (%) at depth x, E_{max} is the maximum seedling emergence percentage (%), x_{50} is the depth at which 50% seedling emergence is achieved, and E_{rate} is the slope of the curve.

$$E(\%) = Emax/\,(1 + exp\,(-(x - T50)/b))\ldots\ldots\ldots\ldots\ldots 4;$$

Where E (%) is the total seedling emergence percentage (%) at time x, E_{max} is the maximum seedling emergence percentage (%), T_{50} is the time to reach 50% of maximum seedling emergence, and E_{rate} indicates the slope.

Results and Discussion

Wild sunflower phenological stages, growth, and seed production

Phenological stages

The number of days required to reach each growth phase varied significantly ($P \leq 0.001$) between locations. Overall, the time required to complete each stage at Adamitulu was significantly less than at Melkassa (Table 1). Studies, also showed that plant age often varies among sites, with unknown effects on phenology (Bertin, 2008); where the difference in key environmental factors like rainfall among locations could have an impact. Dry conditions could accelerate the development of parthenium weed and shorten its life span (Nguyen *et al*., 2017). The periodicity of various events in response to the climatic conditions provides an estimation of the invasive potential of *P. hysterophorus* (Kaur *et al*., 2017).

Amongst the different physiological stages, at both locations, we noticed a prolonged period between the seedling and vegetative stages, as well as between flowering and maturity. This could be due to the high rainfall and low temperature during the vegetative stage and high temperature at the reproductive stage (Fig. 1). High rainfall and low temperature might have favored a prolonged vegetative period and high temperature might have favored flower initiation. Earlier studies showed that the optimum temperature and high humidity favor the growth of *P. hysterophorus*, but it can survive in any climatic condition (Kaur *et al*., 2017). On the other hand, due to the indeterminate growth habit of wild sunflower, flower heads were formed at different times, which could be the cause for the observed prolonged flowering phase. In comparison to determinate plants, indeterminate plants had a longer overlap period between the vegetative and reproductive phases (Zanon *et al*., 2016).

In both locations, wild sunflower took the shortest time to reach the seedling stage. Though the difference between locations for the seedling stage was only about a day, the difference was statistically significant (Table 1). The number of days required for the plant to achieve the vegetative phase varied considerably between locations. It took nearly 51 days at Adamitulu and 60 days at Melkassa. The results also indicated that wild sunflower took an average of 70±4.3 days from seedling emergence to bud formation or flower initiation at Adamitulu and 79±3.6 days at Melkassa (Table 1). The longer period at Melkassa could be attributed to the higher rainfall at this location during the study period (Fig. 1). Similarly, a previous study showed that parthenium weed growing at half of their soil water-holding capacity began flowering at 36 days, while those growing at full soil water-holding capacity began flowering at 44 days (Bajwa *et al*., 2017). In general, wild sunflower took about 128.2±4.8 and 141.2±3.8 days from emergence to maturity at Adamitulu and Melkassa, respectively. Taylor *et al*. (2020) reported that wild sunflower transitioned from leaves to seed drop in an average of 76 days and that the time required varied throughout the year, ranging from 31 to 175 days.

Knowledge of weed phenological stages may assist in the development of management strategies. Taylor *et al*. (2020) observed that control actions were crucial during periods of rapid wild sunflower growth, and further noted the need of incorporating plant phenology data into invasive plant management plans. Wallace *et al*. (2016) also reported the need of understanding the phenological stages to implement the different weed control options successfully on the weed *Pennisetum ciliare*. According to Sade *et al*. (2007), post-emergence herbicides were only effective when applied during the 2-4 leaf stage of the wild sunflower.

Table 1. Growth and reproductive parameters of wild sunflower at different developmental stages at Adamitulu and Melkassa (Means ± Standard error), 2022.

Location	Stages	Duration (days)	Plant height (cm)	Biomass (g plant^{-1})	Branch plant^{-1}	Head plant^{-1}	Seed plant^{-1}
Adamitulu	Seedling	16.55 ± 0.28	8.33 ± 0.26	1.22 ± 0.08	-	-	-
Melkassa		17.45 ± 0.34	9.50 ± 0.43	1.90 ± 0.13	-	-	-
	P-value	***	*	***			
Adamitulu	Vegetative	50.50 ± 3.80	41.11 ± 2.98	8.18 ± 1.30	8.55 ± 2.20	-	-
Melkassa		59.95 ± 2.20	66.35 ± 3.57	12.24 ± 1.31	11.85 ± 2.20	-	-
	P-value	***	***	***	***		
Adamitulu	Bud formation	70.00 ± 4.30	58.38 ± 3.69	12.23 ± 1.19	8.60 ± 1.28	6.40 ± 1.28	-
Melkassa		79.00 ± 3.55	70.52 ± 2.50	14.48 ± 1.29	15.85 ± 1.23	9.05 ± 1.18	-
	P-value	***	***	***	***	***	
Adamitulu	Flowering	92.75 ± 1.73	67.23 ± 2.51	25.95 ± 3.28	12.00 ± 0.85	20.60 ± 1.35	-
Melkassa		97.55 ± 1.85	81.70 ± 3.55	34.76 ± 2.31	22.25 ± 1.23	31.45 ± 3.79	-
	P-value	***	***	***	***	***	
Adamitulu	Maturity	128.20 ± 4.79	67.08 ± 2.61	33.53 ± 2.43	9.64 ± 2.20	9.95 ± 1.20	813.00 ± 74.31
Melkassa		141.15 ± 3.80	81.00 ± 3.60	44.19 ± 1.93	12.60 ± 1.37	18.40 ± 1.41	1124.00 ± 86.23
	P-value	***	***	***	***	***	

Note: *** significant at 0.001; * significant at 0.05

However, mechanical control such as physical removal of flower heads and disposal in sealed bags is regarded as a feasible control method (Shluker, 2002; EPPO, 2012).

Height, branch, and flower head

The height of wild sunflower differed significantly between the two locations. In general, heights were shorter at Adamitulu than at Melkassa for all stages of growth. Plants attained the maximum height at the bud formation stage in both locations (Table 1). The height of wild sunflower increased at an increasing rate as it progressed from the seedling stage to the vegetative stage and then gradually increased up to the flowering stage (Table 1). Wild sunflower started producing branches during the vegetative stage and continued to do so progressively until flowering when it produced the maximum number (22.3±1.2) of branches at Melkassa. The number of branches was lower at Adamitulu than at Melkassa. At both locations, the number of flower heads per plant followed the same trend as the number of branches per plant. Significantly higher number of flower heads per plant (31.5±3.8) was observed at Melkassa than at Adamitulu (20.6±1.4) (Table 1). The results of this study are likely to be strongly influenced by rainfall (i.e. available moisture due to rainfall). Parthenium weed produced more branches, leaves, and shoot length when grown in soil with adequate moisture content, whereas when the soil moisture content was reduced by half, the numbers of branches and leaves were significantly reduced(Bajwa *et al*., 2017).

Biomass and seed production

Biomass accumulation in wild sunflower was observed to be dependent on the growth stage. It increased progressively from the seedling to the maturity stage. Biomass was highest at maturity in both locations. Although the overall pattern was similar, the biomass at Melkassa was significantly higher than that at Adamtulu for all phenological stages. A rapidly increased rate of biomass production was also observed as the stages progressed from seedling to vegetative and flowering to maturity. Moreover, the biomass of wild sunflower was highest (44.2±1.9 g and 34.8±2.3 g) at Melkassa during maturity and flowering, respectively. Likewise, the biomass at Adamitulu was (33.5±2.4 g and 25.9±3.3 g) during the maturity and flowering stages, respectively.

There were significant differences in the number of seeds ($P \leq 0.001$) among locations. The highest number of seeds was recorded from Melkassa (1124 ± 86.2) compared to Adamitulu (813 ± 74.3). Results on the number of seeds recorded is in agreement with Feenstra and Clements (2008) who reported 600–2100 seeds per plant (Feenstra and Clements, 2008).

Biomass and seed production, like phenological stages and growth parameters, may be influenced by environmental factors like rainfall. For instance, soil moisture stress was observed to have an adverse effect on parthenium weed seed production and related traits, resulting in a 50% reduction in seeds when grown in soil with half the maximum soil water holding capacity (Bajwa *et al*., 2017). The difference in weed biomass between locations was significant for each stage, with greater differences at flowering and maturity. This may demonstrate the significance of temperature and moisture at these stages. It is known that the flowering and reproductive stages of plant growth are the most vulnerable to moisture deficit (Asif and Camaran, 2011). According to Prevey and Seastedt (2015), the seed production potential of *Bromus tectorum* was significantly influenced by rainfall.

Seedling Emergence in Relation to Ploughing and Seasons

A significant variation was observed in the number of wild sunflower seedlings that emerged in different seasons and locations. A significantly higher number of seedlings was recorded from unploughed than ploughed plots for both locations (Table 2). On average, seedling emergence m^{-2} under unploughed conditions was 42.6 at Melkassa and 34.4 at Adamitulu; whereas it was reduced to 23.8 and 20.6, at the respective locations, when the plot was ploughed (Table 2).

Table 2. Effects of locations and soil ploughing conditions on wild sunflower seedling emergence in a two-way interaction

Locations	Seedling emergence (m^{-2})	
	Unploughed	ploughed
Adamitulu	34.42^{b}	20.56^{c}
Melkassa	42.56^{a}	23.81^{c}
P value	**	
CV (%)	8.57	
LSD	3.38	

Note: CV-Coefficient of Variation; LSD-Least Significant Difference; ** significant at 0.01

Seedling emergence was higher in summer followed by spring and autumn in both locations (Fig. 2). Seedling emergence was not observed at either location during the dry season under both ploughing conditions and hence data from this season are not shown. This should not be interpreted as a total absence of wild sunflower seedlings during the dry period of the winter season. According to Taleb *et al*. (2011), wild sunflower can produce an enormous number of seeds at any time of the year as long as the optimum moisture and temperature exist.

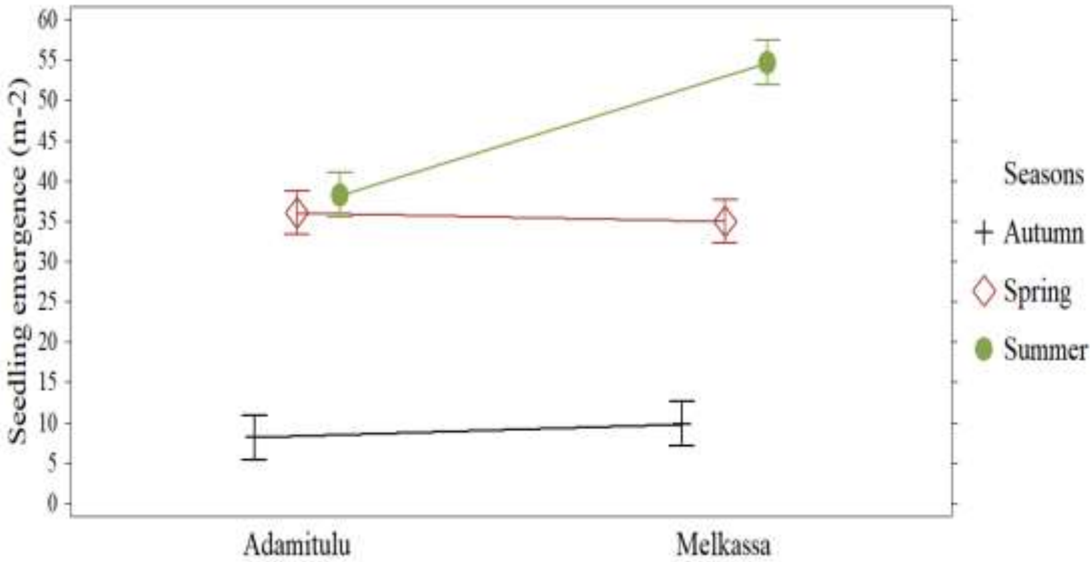

Figure 2.The effect of locations and seasons on wild sunflower seedling emergence

The interaction effect of season and ploughing was significant on wild sunflower seedling emergence (Fig. 3). Ploughed plots in summer had a higher number of emerged seedlings than unploughed plots in autumn. Soil ploughing has a remarkable impact on seedling's emergence by burying the seed deep in the soil, which could explain the higher number of emerged seedlings in unploughed fields than ploughed ones. Previous studies have also shown that tillage affects seedling emergence, which is mainly due to its effects on vertical seed distribution in the soil (Chauhan and Johnson, 2009). Wild sunflower seedlings emerged when moisture was available in undisturbed soil, particularly under fallow conditions. According to Mutti *et al.* (2019), maximum germination of weed seeds and emergence was observed with seeds placed on the soil surface.

Environmental conditions, particularly temperature and rainfall, play an important role in seedling emergence throughout the year. There was a significantly positive correlation between the number of wild sunflower seedlings that emerged and the mean temperature and rainfall at both locations (Table 3). However, at both locations, seedling emergence had a weak negative correlation with maximum temperature (Table 3). Wild sunflower seeds could germinate in a range of temperatures, but too high may halt seed germination. Like any other plant, wild sunflower requires the optimum temperature to germinate or emerge. This could explain why seedling emergence showed a strong positive correlation with mean temperature (Table 3). Relationship with rainfall was also positive and significant in both locations (Table 3).

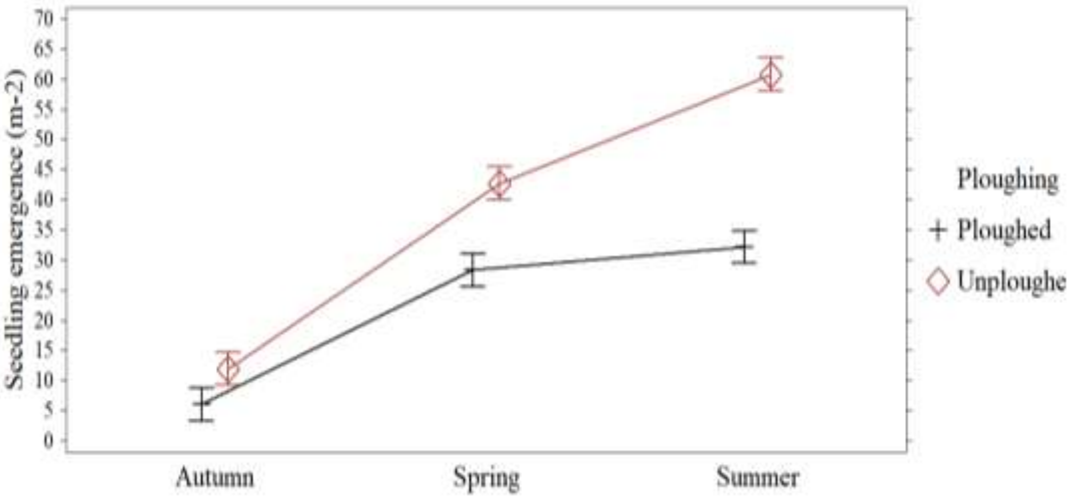

Figure 3. The effect of season and ploughing conditions on the emergence of wild sunflower seedlings

In general, temperature and rainfall play an important role in weed germination and seedling growth. According to Taleb *et al*. (2011), the seed of wild sunflower can germinate at temperatures ranging from 8 to 35 °C (the optimum being 15–25 °C). Another study also indicated that the germination percentage of the seeds amplified and then declined in the temperature range of 15 to 35 °C (Yue *et al.*, 2021), indicating that temperature would be an essential element in weed seed germination (Chauhan and Johnson, 2008). Soil moisture content is also an important factor for annual species seedling emergence, and the wild sunflower reportedly withstands slightly elevated moisture stress (Goyal *et al*., 2019).

Table 3. Correlation of wild sunflower seedling emergence with different environmental factors

Variables	Seedling emergence	
	Adamitulu	Melkassa
Rainfall (mm)	0.79**	0.77**
Maximum Temperature (°C)	-0.53	-0.47
Minimum Temperature (°C)	0.66*	0.62*
Mean Temperature (°C)	0.89***	0.78**
No of rainy days	0.39	0.46
Relative humidity	0.48	0.52

*** significant at 0.001; ** significant at 0.01; * significant at 0.05

Effect of Seed storage time on germination

The percentage of wild sunflower seed germination varied significantly ($P \leq 0.001$) under different seed storage times. The highest percentage of germination (96.9%) was observed from seeds stored for 24 months and the lowest (2%) from freshly harvested seeds (Table 4 and Fig. 5). This could be due to one or more seed dormancy mechanisms that control seed germination. A sharp increase in percent germination was observed in seeds stored for a 0 to 10 weeks storage period. Percent germination after a 10 weeks storage period did not show a marked difference between storage times (Fig. 4). This agrees with reports of Sumudunie and Jayasuriya (2019) who experimented on seed germination of *Ludwigia decurrens.*

As predicted from the fitted model, the storage time required for 50% seed germination was projected at 2.8 weeks (Fig. 4). Moreover, the time to 50% seed germination (T_{50}) for seeds stored for two weeks was 6.2 days, and it decreased as storage time increased (Table 4). It was confirmed that all of the stored seeds began germination on the third day after sowing, whereas the freshly harvested seeds started to germinate on the fifth day (Fig. 5). It was also verified that the maximum germination occurred from day 8 to 10 after sowing for all stored seeds (Fig. 5).

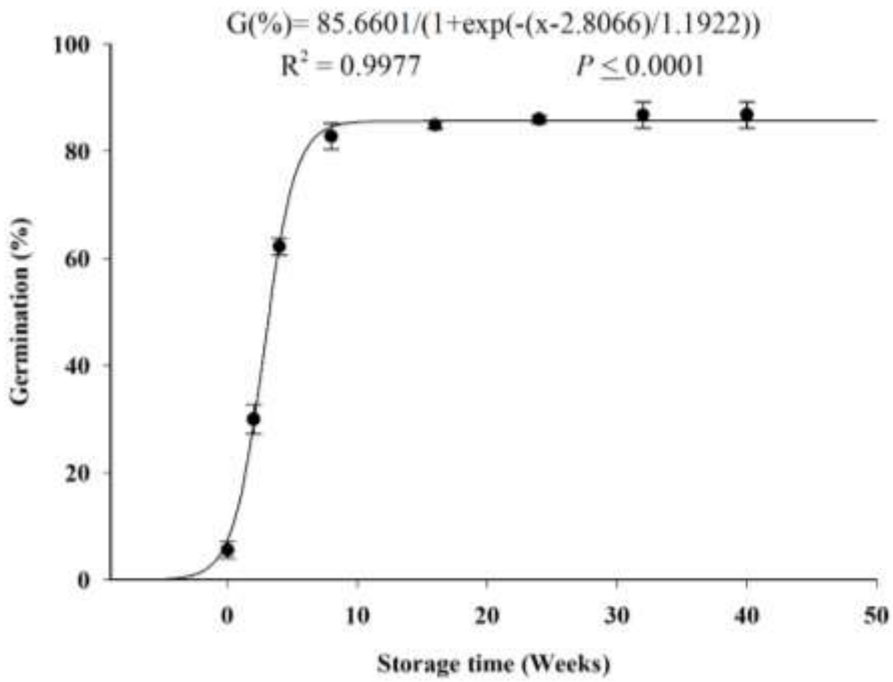

Figure 4. Effect of storage time on the germination of wild sunflower. Vertical bars represent standard error of the mean and three parameter sigmoid regression fit to the data.

Our current study clearly illustrated that, under favorable conditions, wild sunflower seeds have a very short seed dormancy period. Earlier studies depicted that the optimum moisture content for wild sunflower seed germination is 21%, but seeds may remain dormant if the moisture content is less than 5% and temperatures are between 38 and 46 ºC (Kaul and Mangal, 1987). According to the results of this study, it only took about three weeks to achieve 50% germination (Fig. 4), implying that management practices should be implemented before the seed sets or the seed departs from the mother plant. Nevertheless, the low germination percentage with freshly harvested seed suggests that the weed may be dormant for the first 2 weeks after being separated from the mother plant. Recent studies have also revealed that high dormancy is common with freshly harvested seeds (Chauhan, 2022). Another study also revealed that weed seed germination is influenced by different factors, including environmental conditions during storage; such factors are also likely to influence sugar sensitivity during the initial stage of seedling growth (Bas and Sjef, 2007).

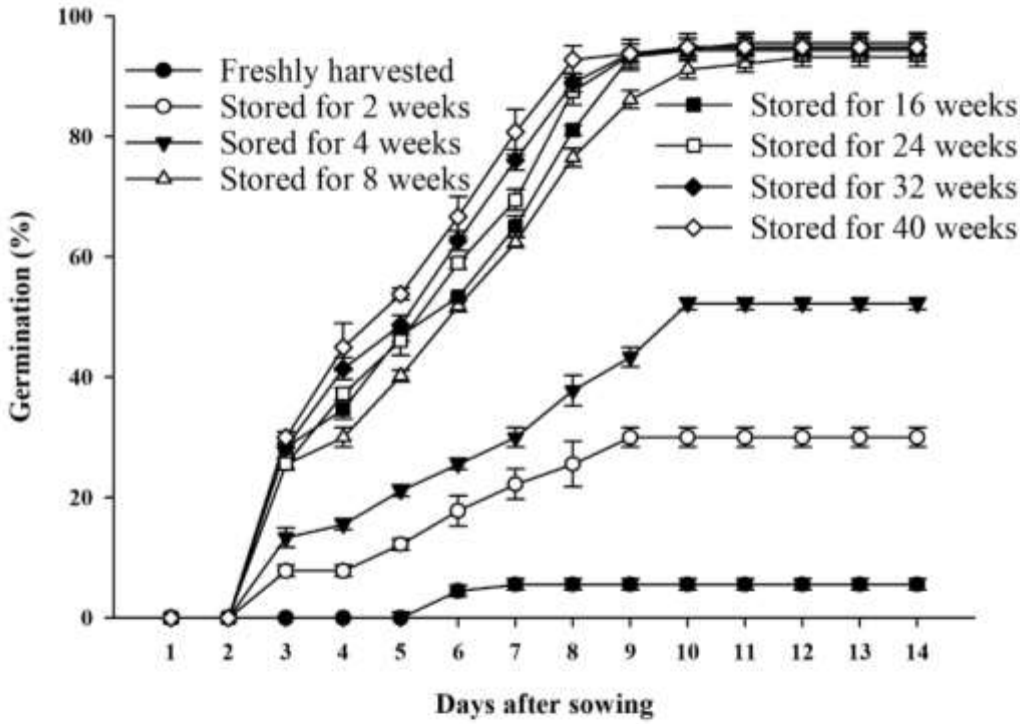

Figure 5. Effect of storage time on daily germination of wild sunflower seeds. Vertical bars represent standard error of the mean.

Table 4. Parameter estimates (G_{max}, maximum germination (%); T_{50}, time to reach 50% of maximum germination (d); G_{rate}, slope) of three-parameter sigmoid models ($G = G_{max} / (1+\exp(-(x- T_{50})/ G_{rate}))$) fitted to the seed germination in Figure 5.

Storage time (Weeks)	Parameter estimates (±SE)			
	G_{max} (%)	T_{50} (d)	G_{rate}	R^2
Stored for 2 weeks	30.61 ± 0.07	6.19 ± 0.30	1.92 ± 0.24	0.99
Stored for 4 weeks	54.71 ± 2.25	5.58 ± 0.21	1.67 ± 0.18	0.99
Stored for 8 weeks	95.04 ± 2.77	5.49 ± 0.17	1.41 ± 0.14	0.98
Stored for 16 weeks	96.56 ± 3.28	5.31 ± 0.25	1.63 ± 0.22	0.97
Stored for 24 weeks	96.94 ± 2.62	5.14 ± 0.20	1.49 ± 0.17	0.98
Stored for 32 weeks	95.83 ± 2.54	4.83 ± 0.19	1.40 ± 0.17	0.98
Stored for 40 weeks	95.37 ± 2.43	4.54 ± 0.18	1.29 ± 0.16	0.99

Note: d-days; SE-standard error

Effect of seed burial depth on seedling emergence

The depth of seed burial affected the emergence of wild sunflower seedlings. As burial depth increased from 0 to 6 cm (Fig. 6 and 7), seedling emergence decreased and fit the three-parameter sigmoid model (Equation 3). The lowest percentage of seedling emergence (6.4 ±0.1%) was recorded with seeds planted at 5 cm depth, while no seedlings emerged from seeds buried at 6 cm. An inverse relationship between sowing depth and seedling emergence has been reported for several weed species (Ebrahimi and Eslami, 2012; Honarmand *et al*., 2016; Yue *et al*., 2021), which agrees with our findings. The number of seedlings that emerged decreased slightly as planting depth increased from 0 to 1 cm but decreased dramatically when seeds were planted at a depth greater than 1 cm. As estimated from the fitted model, the planting depth required for a 50% reduction in the maximum seedling emergence was 2.7 cm (Fig. 6). The time required for 50% seedling emergence (T_{50}) for seeds planted on the soil surface was 4.5±0.2 days, whereas increasing planting depth prolonged emergence, causing the time required for 50% seedling emergence to increase (Table 5).

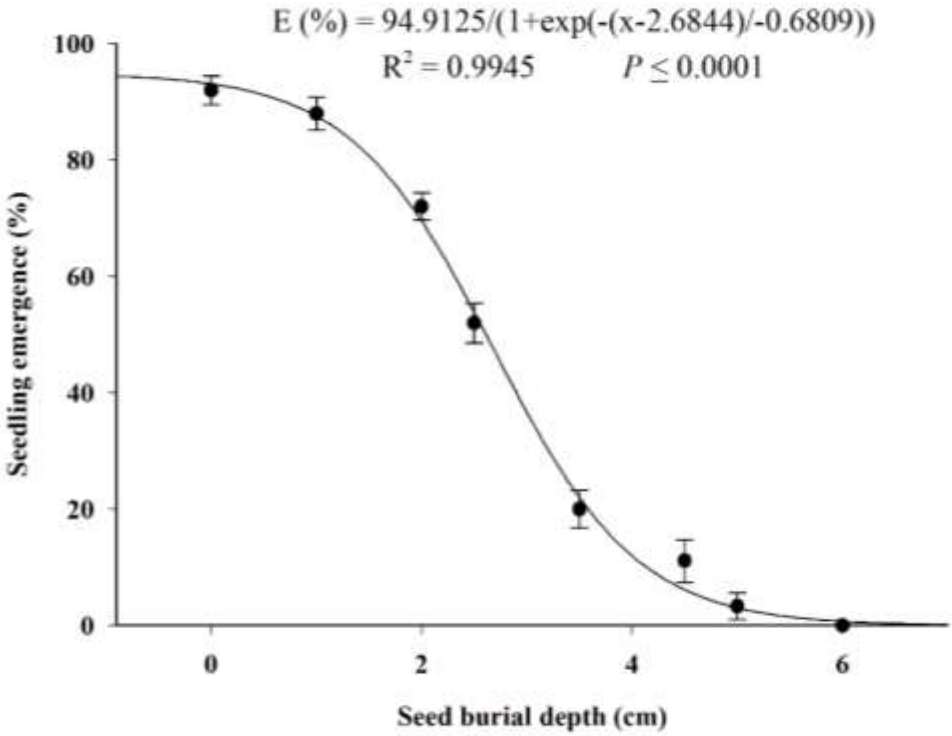

Figure 6. Effect of seed burial depth on the seedling emergence of wild sunflower. Vertical bars represent standard error of the mean and three parameter sigmoid regression fit to the data.

The emergence of wild sunflower seedlings was greatest (93.8±1.5%) when seeds were placed on the soil surface (Table 5). Previous studies on the effect of burial depth on seedling emergence showed that the seed planting depth affected the availability of stored reserves, light, moisture, and temperature (Shoab *et al*., 2012). The highest seedling emergence was observed from surface-seeded seeds (Sade *et al*., 2007; Goyal *et al*., 2019), and no seedlings emerged from sowing depths greater than 2.5 cm (Kaul and Mangal, 1987; Al-Farraj *et al*., 1988). Conversely, 84% reduction in seedling emergence was observed from a depth of 4 cm (Goyal *et al*., 2019). Results of this study suggest that tillage activities that result in seed burial beyond the maximum depth of emergence (i.e., 5 cm) might reduce seedling emergence. The failure of wild sunflower seeds to emerge from the deepest depth could be attributed to their smaller seed size which affects the food reserves (Goyal *et al*., 2019).

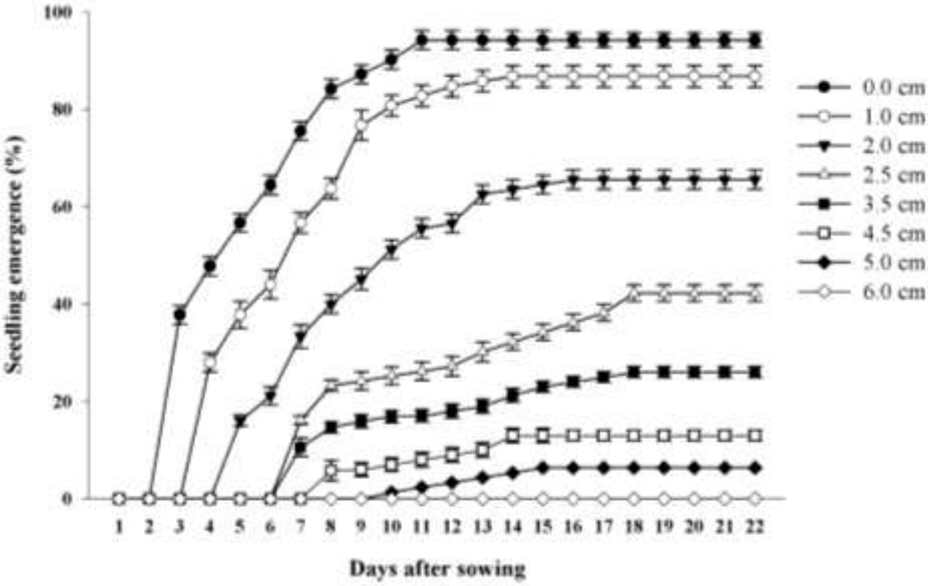

Figure 7. Effect of sowing depth on daily seedling emergence of wild sunflower seeds sown at different soil depths. Vertical bars represent standard error of the mean.

Understanding the effect of soil burial depth on seedling emergence may assist in the use of tillage systems to reduce the number of emerging weed seedlings (Huarte *et al*., 2016; Nosratti *et al*., 2017, 2018). Our results suggest that tillage activities that cause seed burial beyond the maximum depth of emergence (i.e., 5 cm) may reduce seedling emergence.

Table 5. Parameter estimates (E_{max}, maximum emergence (%); T_{50}, time to reach 50% of maximum emergence (d); E_{rate}, slope) of three-parameter sigmoid models ($E = E_{max} / (1+\exp(-(x - T_{50})/E_{rate}))$) fitted to the seedling emergence in Figure 7.

Seed burial depth (cm)	Parameter estimates (±SE)			
	E_{max} (%)	T_{50} (d)	E_{rate}	R^2
0.0	93.76 ± 1.54	4.46 ± 0.19	1.50 ± 0.17	0.99
1.0	86.55 ± 1.27	5.91 ± 0.16	1.55 ± 0.14	0.98
2.0	64.85 ± 0.98	7.39 ± 0.16	1.70 ± 0.14	0.99
2.5	40.78 ± 0.91	8.82 ± 0.42	2.08 ± 0.36	0.96
3.5	25.05 ± 0.89	9.32 ± 0.51	2.42 ± 0.42	0.96
4.5	13.12 ± 0.34	9.91 ± 0.29	1.75 ± 0.24	0.97
5.0	6.39 ± 0.08	11.88 ± 0.09	1.17 ± 0.08	0.99

*d-days; SE-standard error

Conclusion and Recommendation

The present study shows a significant difference in phenological stages, as well as other growth parameters and seed production, between study sites. The wild sunflower seedlings' emergence was likely to be greatly influenced by rainfall and temperature. Wild sunflower produces flower heads and seed continuously due to its indeterminate growth habits; as a result, the seeds mature at different times, which may influence the physiological readiness of the seed for germination. Seasons were observed to significantly influence seedling emergence, with higher seedling emergence recorded during the rainy season. On the contrary, seedlings did not emerge in the dry season. Although seedling emergence is largely dependent on rainfall (moisture availability), it has been observed that wild sunflower grows in all seasons. Hence burning the plant during the dryer period could assist in mitigating the impact of the weed. Unploughed conditions seemed to favor wild sunflower emergence compared to ploughed conditions. This could suggest that no-till systems may favor the emergence of wild sunflower seeds. The maximum (97%) seed germination observed from the prolonged storage time suggests that the wild sunflower may remain dormant by retaining viability until favorable conditions are created. However, the freshly harvested seeds were dormant for a short period, with only 2% germination. Thus, controlling the weed at an early stage before seed setting or removing the weed before the seeds fall into the soil seed bank would be important to prevent its spread. The seed placed on the soil surface resulted in the highest (94%) percentage of seedling emergence. A deep tillage implementation that buries seeds below 6 cm depth could be used as an integrated weed management component to deplete the seed bank. Weed management decisions for a species are derived from knowledge of its biological and ecological features. Thus, the biological and ecological information generated in this study assists in the development of wild sunflower management strategies.

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