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Phenological patterns and the impact of seed burial depth and scarification on the emergence and growth of redweed (*Melochia corchorifolia*)

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Research Article

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Abstract

Redweed is a tropical, erect branched herb, and one of the predominant broadleaf weeds affecting upland crops in the Onattukara Sandy Plains of Kerala, India. Experiments were conducted in a screenhouse in Thiruvananthapuram, Kerala, India, to determine the effects of seed burial depth and seed scarification on emergence indices and growth attributes of redweed. Scarification stimulated emergence and resulted in greater values for emergence indices and seedling parameters. The seedling emergence of redweed was influenced by seed burial depth. Shallow seed burial (2 cm) of scarified and non-scarified seeds resulted in greater seedling length (70 cm and 58 cm, respectively), seedling biomass (0.72 g and 0.48 g, respectively), emergence percentage (60% and 32%, respectively), and greater values for other emergence indices. As the depth of seed burial increased from 2 cm, emergence and seedling biomass decreased, exhibiting lower values for the emergence indices. Correlation and regression studies revealed that seed burial depth of scarified and non-scarified seeds greater than 2 cm had a negative effect on seedling emergence and biomass of redweed. Weed biology studies indicated that redweed displayed notable consistency in its phenological traits, regardless of the location where the seeds were collected, as little ecotype variability was observed. Emergence occurred in 6 d, 50% flowering in 44 d, capsule formation in 56 d, and maturity in 76 d. On average, a single plant produced 277 seeds and had a 100-seed weight of 0.31 g. A stale seedbed with shallow tillage or deep plowing to a depth of 10 cm before sowing can be adopted to reduce the infestation of redweed.

Introduction

Redweed, a tropical. erect branched shrub belonging to the Malvaceae family, consistently yields flowers and fruits throughout the year, showcasing widespread distribution across tropical and subtropical regions in Africa, Asia, and Australia. Its short life cycle, prolific seed production, and adaptability to a diverse array of soils have facilitated the extensive infestation of redweed in upland areas. Although it is suited for xerophytic conditions, redweed also exhibits the capability to flourish in both mesophytic and hydrophytic environments. It is a predominant weed in production of rice (*Oryza sativa* L.) and other upland crops, contributing to elevated production costs and substantial yield reductions. Reported yield losses of upland rice due to redweed infestation can reach 67% (De Datta and Llagas 1984).

Redweed is also a predominant broadleaf weed in crops of carrot [*Daucus carota* ssp. *sativus* (Hoffm.)], potato (*Solanum tuberosum* L.) (Yakubu et al. 2006), and intercropping of maize (*Zea mays* L.) and cowpea (*Vigna unguiculata* L. Walp.) in Nigeria (Takim and Fadayomi 2010). Redweed was also identified as a major weed of upland rice in Philippines (Pullaiah 2014), aerobic rice in Malaysia (Sunyob et al. 2015), direct dry-seeded rice (DSR) in Nepal (Chaudhary et al. 2018), and wet and DSR in northwestern Cambodia (Martin et al. 2021). Redweed infestation has been reported in areas of Turkey where cotton (*Gossypium hirsutum* L.) are grown (Jabran 2016), and in soybean (*Glycine max* L.) fields in Indonesia and Thailand (Pullaiah 2014).

Among the various factors affecting weed establishment, seed burial depth and seed scarification are two key variables that can significantly affect the emergence and subsequent growth of weed species. Seed burial depth refers to the vertical placement of seeds within the soil profile, whereas seed scarification involves mechanical or chemical treatments that alter the seed coat to enhance water and oxygen penetration. The depth at which weed seeds are buried in the soil can influence their exposure to factors such as temperature, moisture, and light availability. Seeds buried at different depths may encounter variations in these conditions, leading to differences in seedling emergence and emergence rate. Conversely, seed scarification can break seed dormancy and promote germination by facilitating water absorption and gas exchange. Weed seeds often possess hard seed coats that can act as barriers to water penetration. Scarification methods such as physical abrasion or chemical treatments aim to overcome these barriers, thereby enhancing the likelihood of successful emergence.

Seeds of redweed are typically distributed both on the surface and within soil layers. Disturbance of the soil through tillage and stale seedbed practices can influence the germination and emergence of the seeds. Dormancy in redweed is a result of its hard seed coat (Eastin 1983). Tillage can invigorate germination by seed coat scarification (Chauhan et al. 2006). Chauhan and Johnson (2008) conducted separate experiments in the Philippines over a study period 10 d to assess the effect on seedling emergence of seed burial depth (0 to 10 cm) and seed scarification with concentrated sulfuric acid for different durations (0, 5, 10, 30, 60, 120 and 180 min). The present study, conducted for a period of 31 d, aimed to assess the effect of seed burial depth on seedling emergence and seedling vigor of scarified (mechanical) and non-scarified seeds of redweed. Also, the prevalent ecotype in Onattukara could potentially be different from that in the Philippines. Therefore, a detailed study in this region was essential to better understand the specific emergence patterns and seedling establishment requirements in order to develop effective management strategies for redweed.

Phenological investigations provide insights into the functional patterns of weeds and weed communities, enhancing the precision of estimating when and how weed competition impacts crop yield in specific agronomic systems, and enabling the development of more targeted control measures.

This research aims to explore the interactive effects of seed burial depth and seed scarification on the emergence and seedling growth of redweed. Furthermore, the research is directed toward understanding the developmental phases of redweed, with a focus on systematically analyzing the various growth stages associated with its life cycle. Understanding the optimal burial depth for redweed can provide valuable insights into its ecological preferences and aid in the development of targeted weed management practices. Investigating the effects of seed scarification on redweed emergence can contribute to the development of strategies that exploit seed dormancy mechanisms for more effective weed control.

Materials and Methods

Study Parameters

Trials were conducted in a screenhouse at the College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, India, from March to May 2021. The first trial was conducted from March 10, 2021, to April 9, 2021, and the confirmatory trial was carried out from April 20, 2021, to May 21, 2021. Experiments were laid out in a completely randomized design (CRD) with two factors replicated three times. Three pots were maintained for each treatment per replication. The first factor was seed burial depth (0, 2, 4, 6, 8, and 10 cm), and the second factor was seed scarification (mechanical scarification and no scarification).

Seed capsules of redweed were hand-harvested from a sesame (*Sesamum indicum* L.) field at the Onattukara Regional Agricultural Research Station (ORARS), Kayamkulam, Kerala, India, in February 2021. The field (between 8.93°N to 9.35°N and 76.39°E to 76.69°E at 3.05 m above mean sea level), located in the Onattukara Sandy Plains, had been under rice-rice-sesame rotation for several years and consisted of loamy sand with 86% sand, 6% silt, and 8% clay. Seeds were separated from capsules by hand, allowed to dry for 2 wk at 25 C, sieved to remove extraneous matter, and then stored in airtight plastic containers until experimentation. The thousand-seed weight of redweed was 3.0 ± 0.20 g. Mechanical seed scarification was performed by spreading seeds on a wooden board and rubbing them with emery cloth of grit size 220 (fine grade) moving 10 cm up and down three times based on the technique described by Mobli et al. (2020).

Average maximum and minimum temperatures inside the screenhouse were maintained at 34.0 and 23.3 C, respectively, during the study period. The soil used for the trials was collected from ORARS fields. The soil was sterilized by autoclaving at 121 C and 1.5 atm for 2 h. Cylindrical pots, 22 cm tall and 20 cm in diameter, were used for the study. For the sowing depth experiments, 25 seeds were placed at 0 (soil surface), 2, 4, 6, 8, and 10 cm below the soil surface. This was achieved by filling the pot with soil to the corresponding level below the surface, placing the seeds, and filling the remainder of the pot with soil. The pots were irrigated as needed to maintain adequate moisture for seedling emergence and growth.

Seedlings were considered emerged when the cotyledons protruded above the soil surface. Seedling emergence was counted daily and remained unchanged after 15 d. At 31 d after seeding (DAS), seedlings were removed and root and shoot lengths were measured. Shoots and roots were separated and dried at 65 ± 5 C to a constant moisture content. Shoot and root biomass were recorded and expressed as grams per plant (g plant^{-1}). Emergence percentage (EP), emergence index (EI) (Bench et al. 1991), emergence rate index (ERI) (Esechie 1994), speed of emergence (SE) (Bartlett 1973), seedling vigor index I (SVI I), and seedling vigor index II (SVI II) (Abdul-Baki and Anderson 1973) were determined using the following formulae:

$$\mathrm{EP} = \text{Total number of seedlings emerged}/\text{Total number of seeds} * 100 \qquad [1]$$

$$\mathrm{EI} = (30 * \mathrm{n}_1) + (29 * \mathrm{n}_2) + \cdots + (1 * \mathrm{n}_{30}) \qquad [2]$$

where n_1, n_2, and n_{30} = number of seedlings emerged on the first, second, and subsequent days until the 30th day; and 30, 29, and 1 are weightage assigned to the number of seedlings emerged on the 1st, 2nd and 30th day, respectively.

$$\mathrm{ERI} = (\mathrm{G}_1 * 100)/1 + (\mathrm{G}_2 * 100)/2 + \cdots + (\mathrm{G}_n * 100)/n \qquad [3]$$

where G_1 and G_2 are the emergence percentage on the first and second days after sowing, and G_n is the emergence percentage on the nth day after sowing.

$$\mathrm{SE} = \mathrm{n}_1/\mathrm{d}_1 + \mathrm{n}_2/\mathrm{d}_2 + \cdots + \mathrm{n}_x/\mathrm{d}_x \qquad [4]$$

where n_1 is the number of seedlings emerged on the first day, n_2 is the number of seedlings emerged on the second day, and n_x is the number of seedlings emerged on the xth day; and d_1 is the first day, d_2 is the second day and d_x is the xth day.

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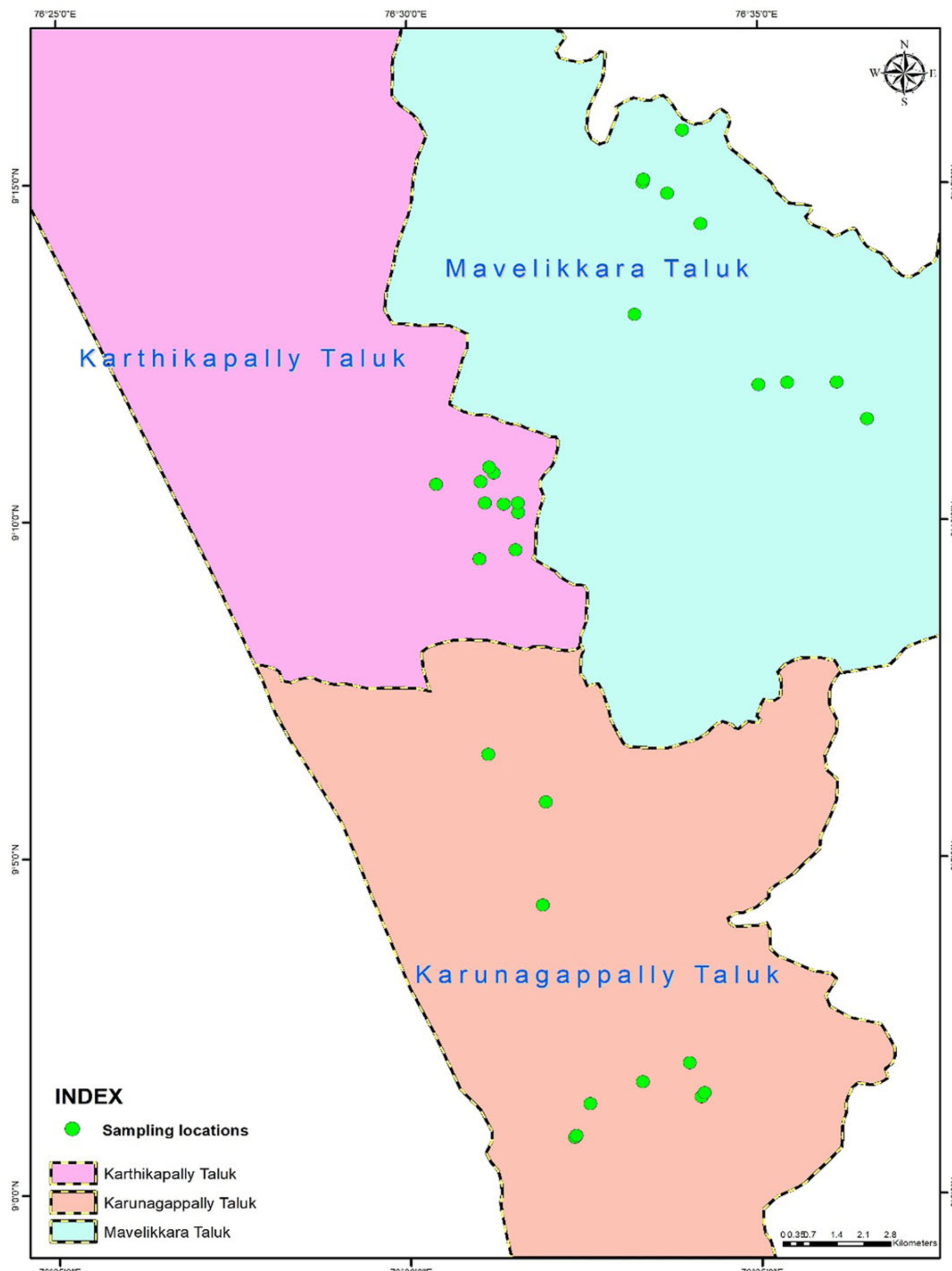

Figure 1. Locations in Karunagapally, Karthikapally, and Mavelikkara regions of India where redweed seeds were collected.

$$\text{SVII} = \text{Seedling length (cm)} * \text{Emergence percentage} \quad [5]$$

$$\text{SVIII} = \text{Seedling biomass (g)} * \text{Emergence percentage} \quad [6]$$

Redweed Biology and Germination Behaviour Studies

Two trials, the first from May 1 to July 20, 2021, and the second from May 10 to July 30, 2021, were conducted in a screenhouse at the College of Agriculture, Vellayani, Thiruvananthapuram, Kerala, India to study the biology and germination behavior of redweed. The average maximum and minimum temperatures inside the screenhouse were maintained at 34.0 and 23.3 C, respectively. Seeds of redweed were collected from 10 distinct locales within the sesame-growing regions of Karthikapally, Karunagapally, and Mavelikkara in the Onattukara Sandy Plains in the Kollam and Alappuzha districts of Kerala, India (Figure 1). Seeds were cleaned and stored as mentioned in the previous study. The pot size was the same as in the previous study and pots were filled with a potting mixture consisting of sterilized river sand and vermicompost (1.5% N, 0.4% P_2O_5, 1.8% K_2O) in a 1:1 ratio. Fifteen scarified seeds of redweed were sown at a depth of 2 cm in

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Table 1. Emergence and vigor indices of redweed as influenced by seed scarification and seed burial depth.[a,b,c]

Seed scarification[d]	Seed burial depth[e]	Emergence indices[f] EP	SE	EI	ERI	Seedling vigor indices[g] SVI I	SVI II
	cm			——— % ———			
Mechanical scarification	0	17 e	0.57 e	94 e	23 e	977 e	9.2 e
	2	60 a	2.25 a	335 a	89 a	4108 a	43.4 a
	4	43 b	1.54 b	248 b	63 b	2848 b	26.3 b
	6	27 d	0.83 d	144 d	35 d	1373 d	12.6 d
	8	9 fg	0.21 fg	45 gh	10 gh	327 fg	2.4 fg
	10	7 gh	0.14 g	31 hi	6 hi	135 h	0.3 h
No scarification	0	8 g	0.34 f	49 g	12 fg	386 fg	3.2 fg
	2	32 c	1.24 c	189 c	42 c	1860 c	15.5 c
	4	25 d	0.81 d	147 d	34 d	1418 d	11.1 de
	6	12 f	0.53 e	68 f	14 f	519 f	4.4 f
	8	7 gh	0.16 g	33 hi	6 hi	196 ghi	0.9 gh
	10	4 h	0.09 g	20 i	4 i	54 i	0.2 h

[a]Abbreviations: EI, emergence index; EP, emergence percentage; ERI, emergence rate index; SE, speed of emergence; SVI I, seedling vigor index I; SVI II, seedling vigor index II.
[b]Means in the table for each parameter is the interaction effect between seed scarification and seed burial depth of pooled data of two trials.
[c]Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ based on Fisher's protected LSD test.
[d]Seed scarification includes mechanical scarification and no scarification.
[e]Seed burial depth includes six different depths of seed burial: 0, 2, 4, 6, 8, 10 cm.
[f]Emergence indices EP, SE, EI, and ERI were calculated by considering the redweed seeds emerged on each day up to 30 d after sowing.
[g]Seedling vigor index SVI I was calculated by considering the emergence percentage and seedling length of redweed, and index SVI II was calculated by considering the emergence percentage and seedling biomass of redweed.

each pot. At 7 DAS, pots were thinned to five plants. Pots were irrigated with an equal quantity of water (1.25 L per pot) twice a week throughout the study. The three regions from which seeds were collected served as treatments and the 10 distinct locales in each region were considered replications.

Statistical Analyses

For both experiments, data from the two trials were pooled and subjected to statistical analysis, because no significant interactions were observed between treatments and the trials. Experimental data were analyzed using the ANOVA technique as suggested by Panse and Sukhatme (1985) with a factorial CRD for the first experiment and CRD for the second experiment. Significance was tested using the *F*-test (Snedecor and Cochran, 1967) and the least significance difference (LSD) was calculated at $P < 0.05$ to denote significant differences. Pearson correlation analysis and regression analysis were conducted to determine the relationships among seed burial depth, emergence indices, and growth parameters. All statistical analyses were carried out using Grapes Agri 1, an open-source R package for agricultural research data analysis, developed by scientists at Kerala Agricultural University and the Indian Agricultural Statistics Research Institute, New Delhi (Gopinath et al. 2021).

Results and Discussion

Effect of Seed Burial Depth and Scarification on Seedling Emergence

Seedling emergence of redweed was first observed at 3 DAS and seed burial depth greatly influenced seedling emergence (Table 1). Fewer surface-placed seeds (0 cm) of both scarified and non-scarified seeds emerged compared with seeds that were buried at depths of 2 cm, 4 cm, and 6 cm, but more than those buried at 8 cm and 10 cm. This reduced emergence might be due to the drying of the upper soil layer, leading to the desiccation of germinated seeds. Ghorbani et al. (1999) suggested that the diminished emergence of surface-sown seeds could be attributed to restricted soil-seed contact, resulting in inadequate water imbibition by the seeds. Chauhan (2016) also observed lower seedling emergence of bladder ketmia (*Hibiscus tridactylites* Lindl.) from surface-placed seeds compared with seeds placed at 1- and 2-cm depths, likely due to reduced seed-to-soil contact and subsequent poor water imbibition.

Seed emergence was affected by seed burial depth and scarification (Table 1). Scarified and non-scarified seeds buried at a depth of 2 cm exhibited the greatest emergence (60% and 32%, respectively). Seedling emergence decreased with increasing depth. The fewest seeds emerged when they were buried at 10 cm, regardless of whether they were scarified (7%) or not scarified (4%), and was 88% less than seeds buried at 2 cm. This might be due to the increased energy demand for emergence at greater depths, which could have resulted in reduced shoot growth. Benvenuti et al. (2001) reported a decrease in seedling emergence as seed burial depth increased. Shallow seed burial (0.5 to 2 cm) of little mallow (*Malva parvifolia* L) resulted in 60% to 62% seedling emergence, with further increases in depth leading to reduced emergence (Chauhan et al. 2006). A previous study of redweed (*Melochia concatenate,* synonym *Melochia corchorifolia*) indicated that the highest of seeds emerged when they were buried at depths of 0 to 2 cm, progressively decreasing with increasing depth, with no emergence at 8 cm (Chauhan and Johnson, 2008).

The present study also found a decrease in emergence with increasing burial depth. However, in contrast to the findings reported by Chauhan and Johnson (2008), we observed that surface-placed scarified and non-scarified redweed seeds exhibited lower emergence (17% and 8%, respectively). Both scarified and non-scarified seeds, however, exhibited greater emergence at a 2 cm depth via a fourfold increase compared with surface-placed seeds. Furthermore, emergence of scarified and non-scarified redweed seeds was observed at 8 cm and 10 cm depths in the present study, contrasting with the previous findings by Chauhan and Johnson (2008) of no emergence at 8 cm.

Physical dormancy is common among Malvaceae species (Harris 1981). The emergence of non-scarified seeds tends to decrease by 46% compared with scarified redweed seeds.

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Table 2. Seedling parameters of redweed as influenced by seed scarification and seed burial depth.[a,b]

Seed scarification[c]	Seed burial depth[d]	Seedling parameters					
		Shoot length	Root length	Shoot biomass	Root biomass	Seedling length	Seedling biomass
Mechanical scarification	——— cm ———			——— g plant^{-1} ———		cm	g plant^{-1}
	0	29 b	28 c	0.36 c	0.17 c	58 c	0.53 c
	2	32 a	38 a	0.44 a	0.28 a	70 a	0.72 a
	4	31 a	37 a	0.39 b	0.23 b	68 b	0.62 b
	6	28 c	25 d	0.31 de	0.17 c	53 e	0.47 d
	8	19 f	16 e	0.18 g	0.08 f	35 h	0.26 h
	10	10 h	11 f	0.03 i	0.01 h	20 j	0.04 j
No scarification	0	21 e	27 c	0.29 e	0.11 e	48 f	0.40 f
	2	26 d	32 b	0.32 d	0.16 c	58 c	0.48 d
	4	25 d	31 b	0.30 de	0.14 d	56 d	0.44 e
	6	20 f	24 d	0.26 f	0.10 e	43 g	0.36 g
	8	14 g	16 e	0.10 h	0.04 g	30 i	0.14 i
	10	7 i	6 g	0.03 i	0.01 h	13 k	0.04 j

[a]Means in the table for each parameter of seedling parameters is the interaction effect between seed scarification and seed burial depth of pooled data of two trials.
[b]Means followed by the same letter within a column are not significantly different at $P \leq 0.05$ based on Fisher's protected LSD test.
[c]Seed scarification includes mechanical scarification and no scarification.
[d]Seed burial depth includes six different depths of seed burial:0, 2, 4, 6, 8, 10 cm.

Mechanical scarification caused abrasion or scratches on the seed coat that enabled the seeds to overcome dormancy by allowing water imbibition. Physically scarified seeds of little mallow exhibited significantly greater emergence (88%) compared with non-scarified seeds (10%) (Chauhan et al. 2006). The greater emergence observed from scarified seeds of redweed compared with non-scarified seed might be attributed to improved water imbibition through a weakened seed coat. Enhanced germination due to scarification was reported in Caesarweed (*Urena lobata* L.), another weed in the family Malvaceae (Awan et al. 2014). Seeds of Venice mallow (*Hibiscus trionum* L.) exhibited greater seedling emergence when buried at a depth of 2 cm (54%) compared with surface-placed seeds (38%) (Chachalis et al. 2008).

Effect of Seed Burial Depth and Scarification on Emergence and Seedling Vigor Indices

The depth of seed burial and seed scarification affected emergence and seedling vigor indices of redweed. Scarified seeds exhibited greater emergence and seedling vigor indices at all seed burial depths (Table 1). Scarified seeds buried at 2 cm produced the greatest EI, ERI, SE, SVI I and SVI II values (Table 1). Conversely, non-scarified redweed seeds buried at 10 cm exhibited lower emergence indices, including EI, ERI, and SE; and seedling vigor indices SVI I and SVI II, which were comparable to those of non-scarified seeds buried at 8 cm (Table 1).

The speed of emergence indicates the total number of seeds that germinate and emerge within a given time interval; greater values indicate greater and faster emergence. Compared with seeds buried at 2 cm, a 93% reduction in the speed of emergence was observed from seeds that were buried at 10 cm. The EI and ERI values also declined by 90% and 92%, respectively, compared with seeds buried at 2 cm. Greater emergence indices from scarified and non-scarified seeds are related to the availability of seed storage reserves for seedling growth. Lower values for emergence indices as noted in seeds buried below 6 cm (Table 1) could be attributed to the depletion of available seed food reserves as the seedlings grow toward the soil surface. According to Benvenuti et al. (2001), the average emergence time (6.8 d) for velvetleaf (*Abutilon theophrasti* Medicus) was less for seeds positioned at 2 cm compared with seeds buried at 10 cm, for which average emergence time was 19.7 d. The emergence index and mean emergence time decreased with increasing seeding depth beyond 2 cm in field bindweed (*Convolvulus arvensis* L.) (Tanveer et al. 2013). An increase in burial depth beyond the tolerable limit would inhibit the normal growth and development of plants (Sun et al. 2010). Greater seedling vigor index values observed at 2 cm seeding depth from scarified and non-scarified seeds were due to greater seedling length and biomass (Table 2). Seeds of whitebark senna [*Senna spectabilis* (DC) H.S. Irwin Barnby] buried at 2 cm exhibited greater SVI values (Sikuku et al. 2018). Both scarified and non-scarified seeds positioned on the surface (0 cm) produced lesser emergence index values compared with those buried at 2 cm in (Table 1). Surface soil does not provide adequate humidity for seed germination and growth (Guo et al. 2010); also, seeds on the soil surface had little chance to germinate due to low soil moisture caused by evaporation (Liu et al. 2011).

Scarification had a significant effect on the emergence indices of redweed. Non-scarified seeds exhibited a decrease in EI, ERI, SE, SVI I, and SVI II values of 44%, 50%, 42%, 55%, and 62%, respectively, compared with scarified seeds. Redweed exhibits notably low emergence indices in the absence of scarification treatment. Malvaceae species commonly exhibited physical dormancy, as noted by Harris (1981). Scarification can break down exogenous dormancy by permeabilizing the seed coat, facilitating water imbibition and embryo expansion (Huang et al. 2017; Matilla 2008).

Effect of Seed Burial Depth and Scarification on Seedling Parameters

Seed burial depth and seed scarification affected the emergence and development of redweed seedlings. Variation in seedling length was observed in response to changes in burial depth in both scarified and non-scarified seeds; however, greater values were observed in scarified seeds (Table 2). Scarified seeds buried at 2 cm produced longer shoots and roots compared with seeds planted at deeper depths (6, 8 and 10 cm) but were on par with scarified seeds placed at 4 cm. Seedling length was greater in scarified seeds placed at 2 cm than those at deeper depths (Table 2). Seedlings that emerged from non-scarified seeds buried at 10 cm exhibited markedly small shoots, roots, and overall seedling lengths (Table 2).

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Surface-placed seeds (0 cm; both scarified and non-scarified) exhibited shorter seedling length compared with seeds buried at 2 cm and 4 cm (Table 2). Surface-placed seeds (0 cm) are subjected to regular soil drying due to moisture loss through evaporation. Sowing to a depth of 2 cm proves advantageous by offering seeds prolonged access to moisture. Consequently, this extended moisture availability enables seedlings to develop deeper root systems, facilitating access to water sources at greater depths. These results align with those reported by Awan et al. (2014) that surface-placed Caesarweed recorded lesser seedling biomass than those placed at 1 cm. A decrease in seedling length by 74% of redweed was exhibited by seeds positioned at a depth of 10 cm compared with those at 2 cm. Seeds with larger food reserves can generate long hypocotyls, aiding their emergence above the surface. The decline in shoot length with increasing seed burial depth suggests that seeds may have used their endosperm for growth while growing toward the soil surface. Deeply buried seeds did not have adequate energy reserves for the seedlings to grow to the surface (Jorgensen et al. 2019).

The depth at which seeds were buried and seed scarification affected shoot, root, and biomass of redweed seedlings (Table 2). Seedlings that emerged from scarified seeds buried at a depth of 2 cm exhibited greater shoot, root, and overall seedling biomass. Seedling biomass, did not vary significantly between scarified and non-scarified seeds placed at 10 cm, although the biomass of these seeds was lower than seeds that were buried at shallower depths.

A reduction of 93% in the seedling biomass of redweed was observed in seeds placed at 10 cm, compared with seeds placed at 2 cm depth. The reduction in seedling biomass in seeds buried at deeper depths might be due to a lack of sufficient oxygen, light, moisture, and temperature, the factors that are essential for plant growth (Soltani et al. 2013). The reduction in the number of leaves and leaf area, as a result of depleted seed endosperm reserves and the lack of oxygen and light at greater depths (8 and 10 cm), may have influenced photosynthesis and dry matter production. Seeds buried at deeper depths were subjected to anoxic conditions and had negative redox values leading to exposure to reduced metabolites and increased seed mortality (Jorgensen et al. 2019). Observations of wild oat (*Avena fatua* L.) indicated a consistent decrease in both shoot and root biomass as burial depth increased. Seeds of wild oat buried at 10 cm exhibited a decline in shoot and root biomass of 60% and 55%, respectively, compared with seeds sown at a depth of 4 cm. The decrease in root biomass with increasing seed burial depth was attributed to reduced light diffusion, elevated mechanical resistance posed by the soil, and decreased seed viability (Maqbool et al. 2020).

Scarification positively affected both seedling length and biomass. In contrast, non-scarified seeds of redweed exhibited a decline in seedling length and biomass by 19% and 30%, respectively, compared with scarified seeds. Increase in shoot and root length and shoot and root biomass) resulted in greater seedling length and biomass (Table 2) in scarified seeds. Scarification allows the seeds to imbibe water quickly (Chauhan et al. 2006), which enhances seedling emergence and enables faster growth.

Pearson correlation analysis revealed a negative correlation between seed burial depth and emergence parameters (Figure 2). Regression analysis investigating the influence of depth on seedling length and biomass of both scarified and non-scarified seeds of redweed revealed highly significant negative regression values (Figures 3, 4, 5, and 6). Regression analysis supported the findings of the study, showing that seedling length and biomass of both sacrificed and non-sacrificed seeds were adversely affected at depths greater than 2 cm, but an increase in seedling length and biomass has been observed from 0 to 2 cm. The regression model for seedling length and seedling biomass of scarified and non-scarified seeds followed a second order polynomial.

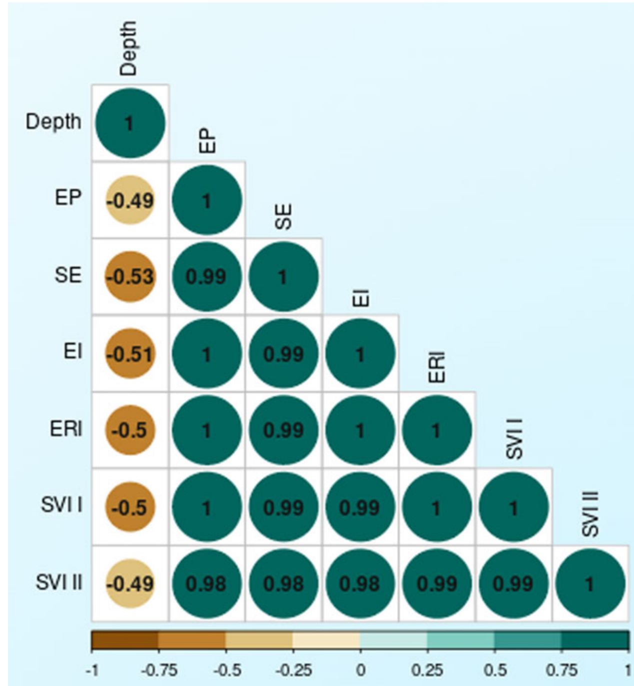

Figure 2. Correlation matrix of seed burial depth, emergence percentage (EP), speed of emergence (SE), emergence index (EI), emergence rate index (ERI), seedling vigor index I (SVI I) and seedling vigor index II (SVI II).

Studies Redweed Biology and Germination Behavior

Redweed displayed notable consistency in its phenological traits regardless of where the seeds were collected. Analysis of growth and yield characteristics unveiled intriguing patterns. Maximum emergence of redweed was observed on the sixth day, with first flowering appearing on the forty-second day, and plants attained a height of 75.6 cm at harvest. On average, a single plant produced 277 seeds, with a 100-seed weight of 0.31 g. Analysis of the growth stages of redweed revealed that on average, the vegetative phase spanned 35 d, with 50% flowering occurring at 44 d, capsule formation at 56 d, and maturity at 76 d.

Engel et al. (2011) reported that changes in environment and soil conditions may cause morphological variability in a species. Precipitation is a major factor determining the functional traits in *Stipa* species (large perennial grasses) (Lu et al. 2016) and Wang et al. (2020) reported that precipitation varies considerably with changes in longitude. The three regions where this study was carried out (Karunagapally, Karthikapally, and Mavelikkara) are located at the same longitude of 76°E, which may explain the lack of variations observed in the growth stages of redweed among these locations.

In summary, experiments demonstrated that shallow burial depth (2 cm) promoted seedling emergence and early morphological development of redweed compared to deeper seed burial depths. Deeper burial negatively affected both seedling emergence and seedling biomass. Scarification consistently improved emergence and biomass across all burial depths, highlighting its role in stimulating seedling emergence. The greater emergence observed

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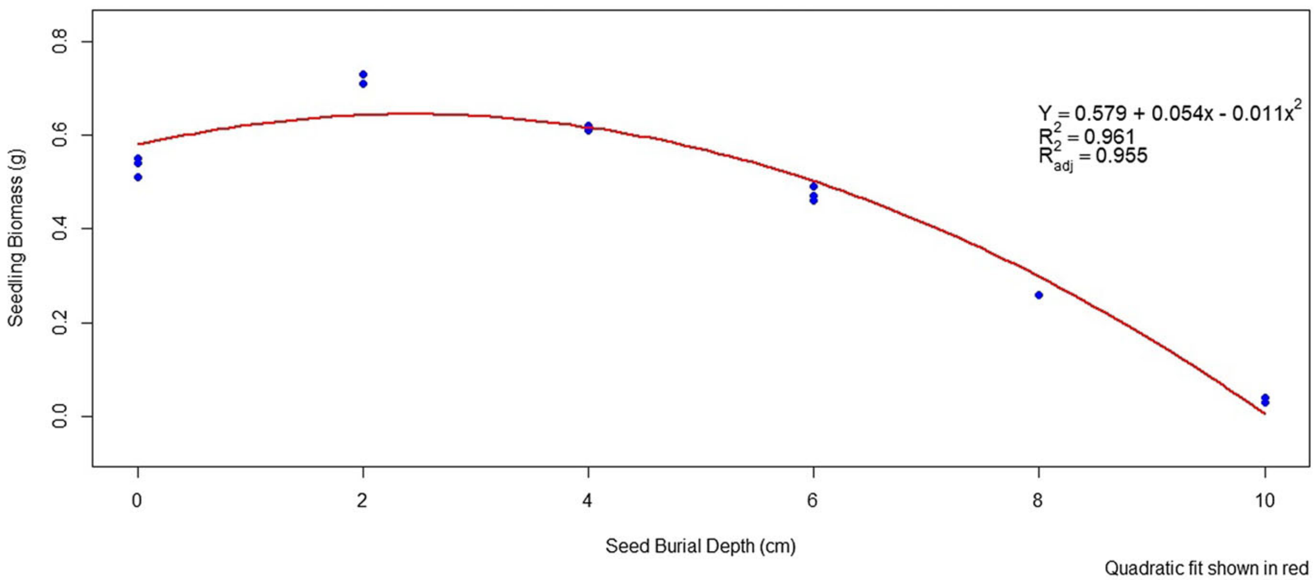

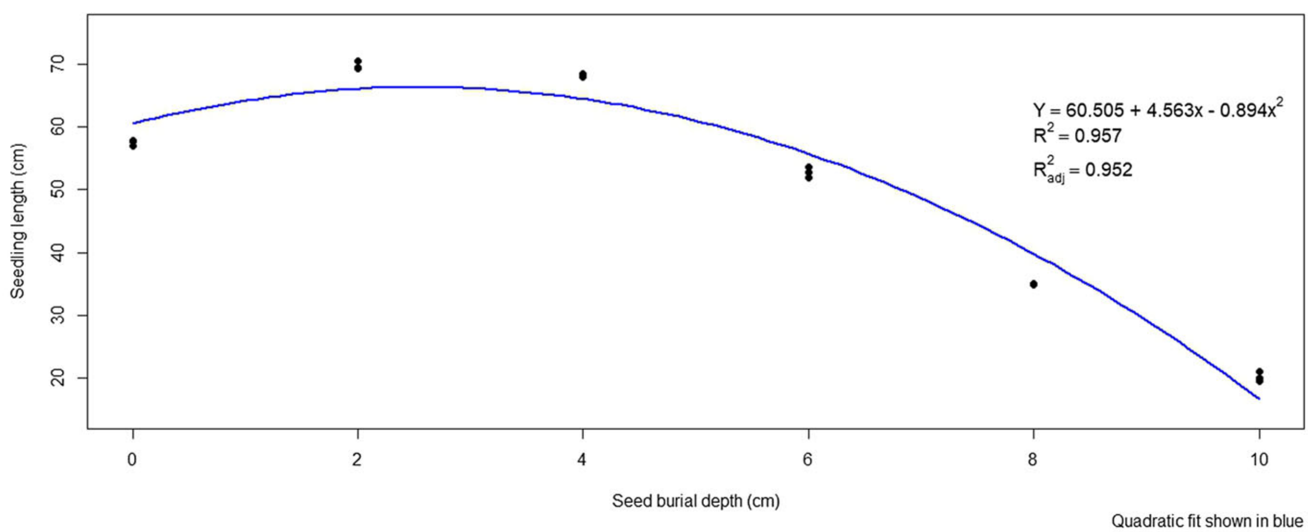

Figure 3. Polynomial regression model depicting the relationship between seed burial depth and seedling length of scarified seeds of redweed.

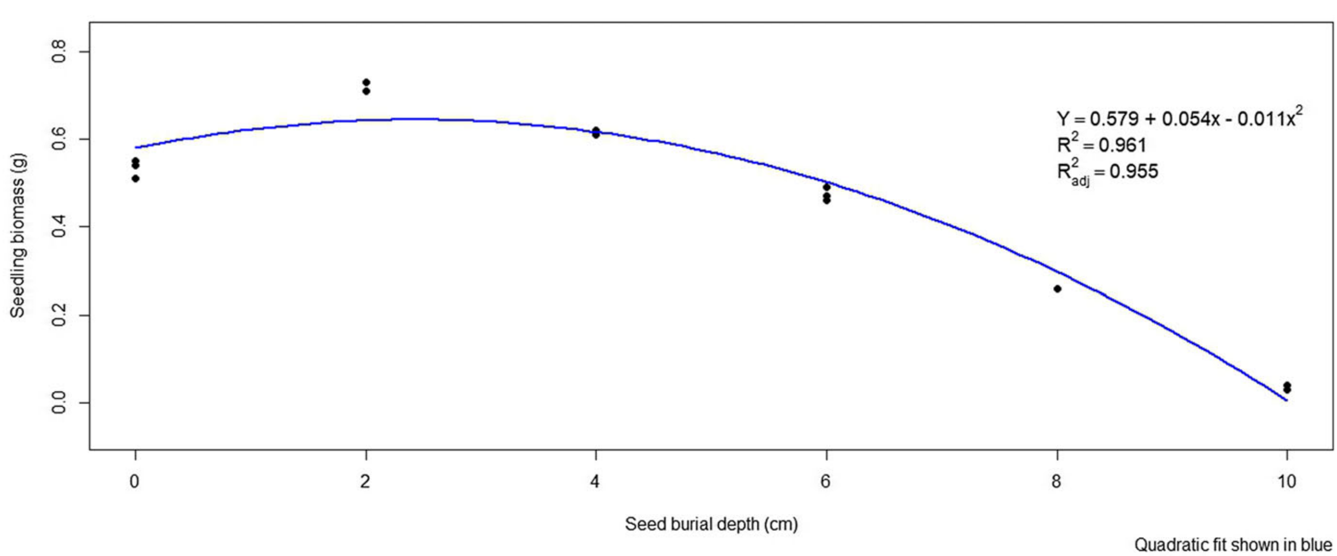

Figure 4. Polynomial regression model depicting the relationship between seed burial depth and seedling biomass of scarified seeds of redweed.

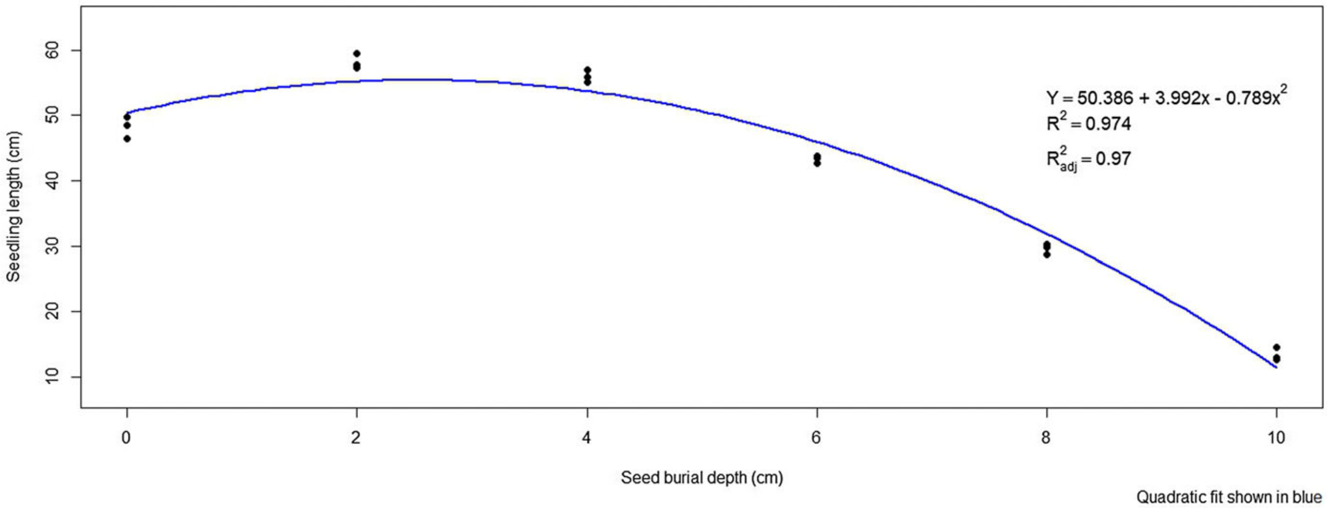

Figure 5. Polynomial regression model depicting the relationship between seed burial depth and seedling length of non-scarified seeds of redweed.

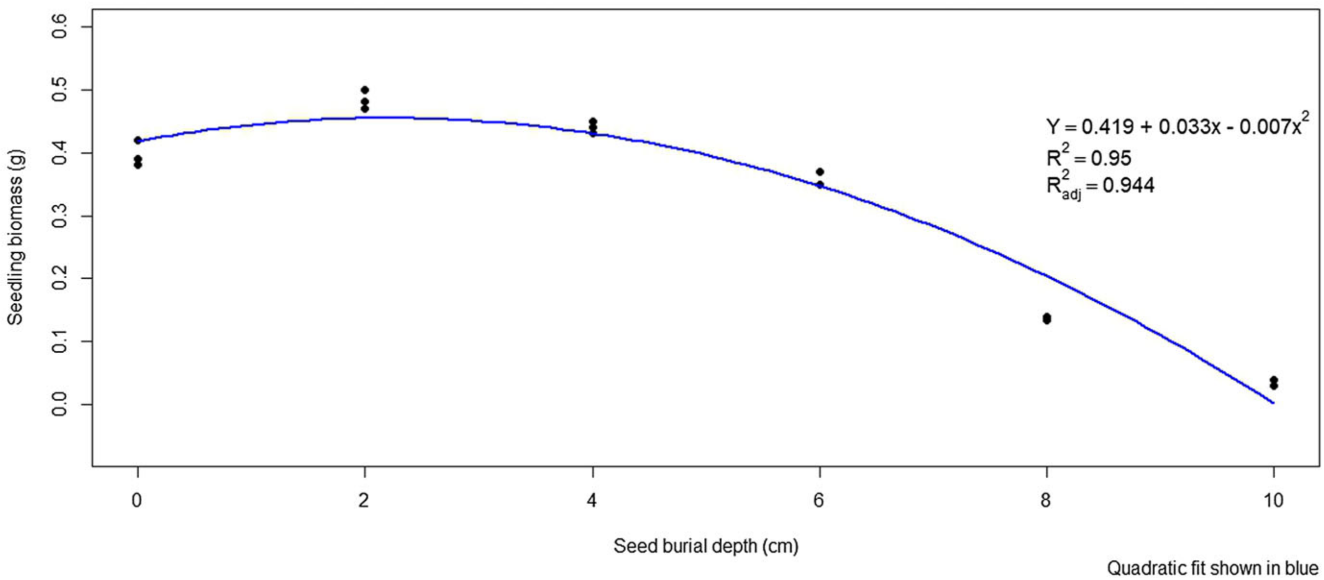

Figure 6. Polynomial regression model depicting the relationship between seed burial depth and seedling biomass of non-scarified seeds of redweed.

from 2 cm suggests that the stale seedbed technique should be emphasized to minimize early crop-weed competition and mitigate yield loss associated with redweed infestation. Additionally, deep tillage operations (burying seeds beyond 10 cm) before the sowing of sesame could help suppress the buildup of the redweed seed bank in the long term.

Practical Implications

Understanding the biology and effects of seed burial depth on redweed helps in designing management practices to reduce weed emergence and develop eco-friendly weed management approaches. Shallow seed burial (2 cm) promotes greater seedling emergence compared to deep seed burials. This suggests that tillage practices to bury seeds deeply (beyond 10 cm) can disrupt seedbank buildup. Deep seed burials negatively affect both emergence and seedling biomass and can potentially suppress weed seedbank establishment. The greater emergence of redweed from 2 cm suggests that the stale seedbed technique, which allows for weed emergence that is subsequently killed with shallow tillage before the sowing of crops, could be a useful strategy to minimize early competition and mitigate yield losses. Mechanical scarification weakens the seed coat and improves the emergence and biomass accumulation of redweed. This suggests that any type of tillage immediately after the crop is sown should be avoided to reduce redweed emergence and avoid crop-weed competition in the early stages of the crop. Integrating knowledge of weed biology, seed burial depth, and scarification can help in developing effective weed management interventions, ultimately helping farmers optimize crop yield while minimizing redweed-related losses.

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