Annals of Arid Zone 64(3): 413-424, 2025

Soil-Specific Optimal Sowing Depth for Coriander: Effects on Seed Germination and Early Growth

Rajan Modhavadia, Kunal N. Odedra*, Jenish Bamaniya and B.A. Jadeja

Department of Botany, M.D. Science College, Porbandar, Gujarat, India

Received: March 7, 2025   Accepted: July 8, 2025

Abstract: Coriander (*Coriandrum sativum* L.) is a commercially and nutritionally important seed spice crop, with India accounting for over 67% of global production and a leading position in export markets. Despite its prominence, suboptimal agronomic practices-particularly inappropriate sowing depth and soil selection-limit successful stand establishment and early seedling vigor. This study investigates the combined effects of sowing depth (0, 1, 2 and 3 cm) and soil type (red, black, sandy, and alluvial) on seed germination and early growth performance of coriander under controlled pot conditions. A total of 160 seeds were tested across 32 treatment units in a completely randomized design. Germination metrics such as germination percentage (GP), mean germination time (MGT), germination index (GI), and coefficient of velocity of germination (CVG), along with seedling height, leaf number, and stem diameter, were recorded over six weeks. The results revealed that a 1 cm sowing depth in black soil yielded the highest germination efficiency (GI = 6.17, CVG = 61.54%, MGT = 1.63 days) and early vigor. Conversely, germination declined markedly at 3 cm depth, especially in sandy and alluvial soils. Although ANOVA results were not statistically significant due to limited replication, logistic modelling and correlation analyses underscored black soil's superior performance across depths and sandy soil's support for enhanced vegetative traits at deeper sowing. These findings suggest that a sowing depth of 1-2 cm, particularly in black or well-drained sandy soils, optimizes both germination kinetics and seedling establishment. Such soil-specific recommendations are crucial for improving coriander productivity in diverse agro-climatic zones.

Key words: *Coriandrum sativum*, sowing depth, soil type, germination index, seedling vigor, stand establishment, edaphic response.

***Correspondence**
Kunal N. Odedra
kunal.n.odedra1@gmail.com

Citation
Modhavadia, R., Odedra, K.N., Bamaniya, J and Jadeja, B.A. 2025. Soil-specific optimal sowing depth for coriander: Effects on seed germination and early growth. Annals of Arid Zone 64(3): 413-424

https://doi.org/10.56093/aaz.v64i3.165757

https://epubs.icar.org.in/index.php/AAZ/article/view/165757

Coriander (*Coriandrum sativum* L.), an annual herbaceous crop belonging to the Apiaceae family, holds significant importance as a seed spice cultivated widely across the globe. India is the foremost producer, consumer, and exporter of coriander, accounting for nearly 67.57% of the global market share as of 2021 (Anonymous, 2022). The country's coriander seed production reached 973.97 thousand tonnes with a gross production value (GPV) estimated at US$ 1.43 billion. During the year 2022-2023, India exported 54.81 thousand tons of coriander, valued at US$ 82.61 million, reinforcing its dominant position in the global coriander trade, with a production share ranging from 76% to 80% (Stat Ledger, 2024). Globally, other notable coriander-producing countries include Turkey, Mexico, and Russia. Within India, the principal coriander-producing states are Madhya Pradesh, Gujarat, Rajasthan, Assam, Odisha, and West Bengal, with Gujarat ranking second in both area under cultivation and total production.

Despite its considerable economic and culinary significance, coriander cultivation in India is often constrained by multiple challenges such as erratic weather conditions, unsuitable soil choices, and suboptimal agronomic practices. A notable issue is the lack of accessible and precise information for farmers regarding ideal soil and climatic conditions, often resulting in poor and inconsistent crop performance (Santhosh *et al*., 2019). Among the agronomic factors influencing coriander growth, sowing depth is particularly critical, as it directly impacts seed germination, seedling emergence, and early plant development.

Seed germination represents a vital physiological phase in a plant's life cycle and is modulated by both genetic makeup and environmental conditions (Shafii and Price, 2001). Successful seedling establishment, governed largely by germination efficiency, is a key determinant of crop yield (Sarkar *et al*., 2020). Factors such as temperature, moisture availability, and soil texture significantly affect germination outcomes and seedling vigor (Gowtham and Mohanalakshmi, 2018). The interaction between sowing depth and these environmental variables can therefore play a decisive role in early plant growth and productivity.

Although coriander's agronomic traits have been studied to some extent, research specifically focusing on the effects of sowing depth on its germination and seedling dynamics remains limited. The bulk of existing literature on sowing depth pertains primarily to cereal and legume crops, with few studies addressing coriander. Moreover, detailed investigations incorporating germination indices-essential for evaluating seed performance under varied sowing conditions-are scarce. This lack of targeted research has resulted in an absence of standardized agronomic recommendations for coriander, particularly with regard to optimal sowing depth.

To address this research gap, the present study investigates the influence of different sowing depths and soil types on coriander seed germination and seedling development. The study specifically aims to determine the optimal sowing depth that maximizes germination percentage and seedling vigor, to evaluate how varying depths affect key germination indices, and to assess the early growth performance of seedlings sown at different depths. The findings are expected to provide scientifically grounded recommendations for coriander growers, thereby facilitating improved seedling establishment and enhanced crop productivity across diverse agro-climatic regions.

Materials and Methods

The present study was conducted at the Department of Botany, Maharshi Dayanand Science College, Porbandar (Gujarat, India) to investigate the effects of sowing depth and soil type on the germination and early growth of *Coriandrum sativum* L. (variety Nidhi-Super 70032). Soil samples were collected from four distinct zones of Porbandar district, each representing a principal soil type. The selected sites included red soil from Sakhpur village (21°48′10.2′′N, 69°28′17.5′′E), black soil from Advana village (21°56′20.2′′N, 69°35′50.1′′E), sandy soil from Kuchhdi village (21°40′57.8′′N, 69°32′23.7′′E), and alluvial soil from Bagvadar village (21°47′05′′N, 69°36′08′′E). At each location, a one-hectare area was delineated for sampling. The zigzag method of soil sampling was employed as recommended by FAO (2004), wherein 8-10 sub-samples were collected from a depth of 0-15 cm using a hand trowel. These sub-samples were thoroughly mixed to prepare a composite sample for each site, which was subsequently stored in labelled polythene bags for use in the experiment.

Seeds of *Coriandrum sativum* (variety Nidhi-Super 70032) were obtained from a certified agro-input supplier and stored in a cool, dry place until sowing. The germination trial was set up using disposable plastic bags (18 ×

12 cm) filled with one of the four soil types. Seeds were sown at four different depths: 0 cm (surface), 1 cm, 2 cm, and 3 cm. Depths were carefully measured with a ruler and marked using an HB pencil on the interior of each bag. Each combination of soil type and sowing depth was replicated twice, and five seeds were sown per replicate. Thus, the experimental setup comprised 32 treatment units (4 soil types × 4 depths × 2 replicates), with a total of 160 seeds. All bags were maintained under ambient conditions with regular watering to ensure adequate moisture.

Observations were recorded over a period of six weeks. Germination parameters assessed included germination percentage (GP), mean germination time (MGT), germination speed (GS), germination index (GI), peak value (PV), and coefficient of velocity of germination (CVG). Germination percentage (GP) was determined using the formula (Al-Mudaris, 1998):

$$GP\ (\%)=(Ng/Nt)\ x\ 100$$

MGT was calculated to assess the average time required for seed germination, using the equation (Prasad, 2024):

$$MGT = (\sum(ni\ x\ ti))/(\sum ti)$$

where, n_i=Number of seeds germinated on day t_i, t_i=Time in days from sowing, $\sum n_i$ = Total number of germinated seeds

GS was determined using the Germination Index (GI), calculated as follows (Evetts and Burnside, 1972):

$$GS = GI/FGP$$

where, GI= Germination Index and FGP= Final germination percentage.

GI was determined based on the weighted germination counts over time (Prasad, 2024):

$$GI = \sum(Gt/Tt)$$

where, G_t = Number of seeds germinated on day T_t, T_t = Time in days

PV was calculated as the highest mean daily germination (Czabator, 1962):

$$PV = N_{max}/D$$

where, N_{max} = Maximum number of germinated seeds recorded on any day, D = Number of days taken to reach the peak germination

CVG was used to measure the speed of germination in percentage terms and was calculated as (Al-Mudaris, 1998):

$$CVG(\%) = [\sum(G)/\sum(G\ x\ T)]\ x\ 100$$

where, G = Number of seeds germinated each day, T = Time in days

In addition to germination traits, seedling growth parameters were also recorded. These included seedling height (measured from soil surface to the tip of the tallest leaf), stem diameter (measured at the base using a vernier calliper), number of leaves per seedling, and canopy area (estimated from leaf length and width). All growth parameters were recorded weekly to monitor developmental trends under different soil and sowing depth conditions.

The collected data were statistically analysed using two-way analysis of variance (ANOVA) to evaluate the effects of soil type and sowing depth on germination and seedling growth traits. Post hoc comparisons of treatment means were performed using Duncan's Multiple Range Test (DMRT) at a 5% level of significance. Correlation analyses were conducted using Pearson's method to determine associations among sowing depth, soil type, germination performance, and seedling development. Additionally, logistic regression models were fitted to germination kinetics data to assess the germination dynamics over time, with the goodness-of-fit of models evaluated using the coefficient of determination (R^2). All statistical analyses were carried out using standard statistical software.

Result and Discussion

The germination response of coriander seeds varied significantly with sowing depth and soil type, as summarized in Table 1. The optimal performance was observed at a sowing depth of 1 cm, where 100% germination was recorded in both red and sandy soils, followed by black soil (80%). In contrast, a notable decline in germination percentage (GP) was observed at 3 cm depth, particularly in sandy (40%) and alluvial soils (20%). Even surface sowing (0 cm) resulted in relatively high germination in black and sandy soils (90%), but alluvial soil showed reduced performance (70%), possibly due to its loose texture and higher susceptibility to moisture loss.

Table 1. Germination parameters of coriander seeds under different soil types and sowing depths

Sowing depth	Soil type	GP (%)	MGT (days)	GI	GS	PV	CVG (%)
0 cm	Red	80.0	5.25	1.53	1.22	1.20	19.05
	Black	90.0	3.67	3.62	3.26	1.25	27.27
	Sandy	90.0	4.67	2.02	1.82	0.67	21.43
	Alluvial	70.0	3.29	3.34	2.34	1.00	30.43
1 cm	Red	100.0	2.50	4.43	4.43	2.50	40.00
	Black	80.0	1.63	6.17	4.94	5.00	61.54
	Sandy	100.0	4.40	2.51	2.51	1.00	22.73
	Alluvial	70.0	4.00	2.15	1.51	0.75	25.00
2 cm	Red	80.0	3.63	2.62	2.10	0.75	27.59
	Black	90.0	3.44	2.59	2.33	1.00	29.03
	Sandy	90.0	5.56	2.07	1.86	0.80	18.00
	Alluvial	50.0	8.80	0.52	0.26	0.25	11.36
3 cm	Red	80.0	5.38	1.85	1.48	1.00	18.60
	Black	100.0	5.90	2.24	2.24	1.00	16.95
	Sandy	40.0	6.50	0.63	0.25	0.43	15.38
	Alluvial	20.0	6.50	0.31	0.06	0.17	15.38

Germination percentage (GP), Mean germination Time (MGT), Germination speed (GS), Germination index (GI), Peak value (PV), Coefficient of velocity of germination (CVG)

The germination index (GI) further illustrated these trends. The highest GI (6.17) occurred in black soil at 1 cm, indicating vigorous and early germination (Table 1). Conversely, GI values declined sharply in alluvial soil at 2 cm (0.52) and 3 cm (0.31) depths. These observations support the hypothesis that deeper sowing impedes oxygen diffusion and increases energy demands for emergence, consistent with findings by Bewley *et al.* (2013).

The peak value (PV), reflecting the uniformity and concentration of germination events, was also highest in black soil at 1 cm depth (5.00), further confirming the superior germination potential under these conditions. In contrast, sandy and alluvial soils at 3 cm showed very low PVs (0.43 and 0.17, respectively), indicating poor synchrony in germination.

The coefficient of velocity of germination (CVG), a reliable index of germination speed, was also maximum in black soil at 1 cm (61.54%), whereas alluvial soil at 3 cm had the lowest CVG (15.38%). These values are indicative of faster and more uniform seedling emergence under favorable depth-soil combinations. Supporting this, the mean germination time (MGT) was lowest in black soil at 1 cm (1.63 days), while the highest MGT was seen in alluvial soil at 2 cm (8.80 days). These patterns reinforce the conclusions of Maguire (1962) that intermediate sowing depths (1-2 cm) facilitate better germination kinetics compared to shallow or deep placements.

Across soil types, black soil consistently outperformed others in supporting germination and seedling growth. This is likely attributable to its higher clay content, water-holding capacity, and good seed-soil contact, which enhance seed imbibition and enzyme activation. At deeper depths, black soil maintained high GP (90-100%), underscoring its suitability for sowing even under sub-optimal placement. Conversely, alluvial soil showed sharp declines in germination beyond 1 cm, reflecting its porous structure and reduced moisture retention. These observations are in line with Martínez (1992), who emphasized the role of soil structure and moisture regime in determining seed-soil interactions.

Despite these evident trends, two-way ANOVA results revealed no statistically significant main effects of sowing depth or soil type on any germination parameter (GP, GI, GS, PV, CVG, MGT), with all p-values > 0.05. Marginal trends were observed for sowing depth on MGT and GI ($p = 0.07$), and for soil type on GP ($p = 0.07$), suggesting a possibility of biological relevance without statistical significance, potentially due to

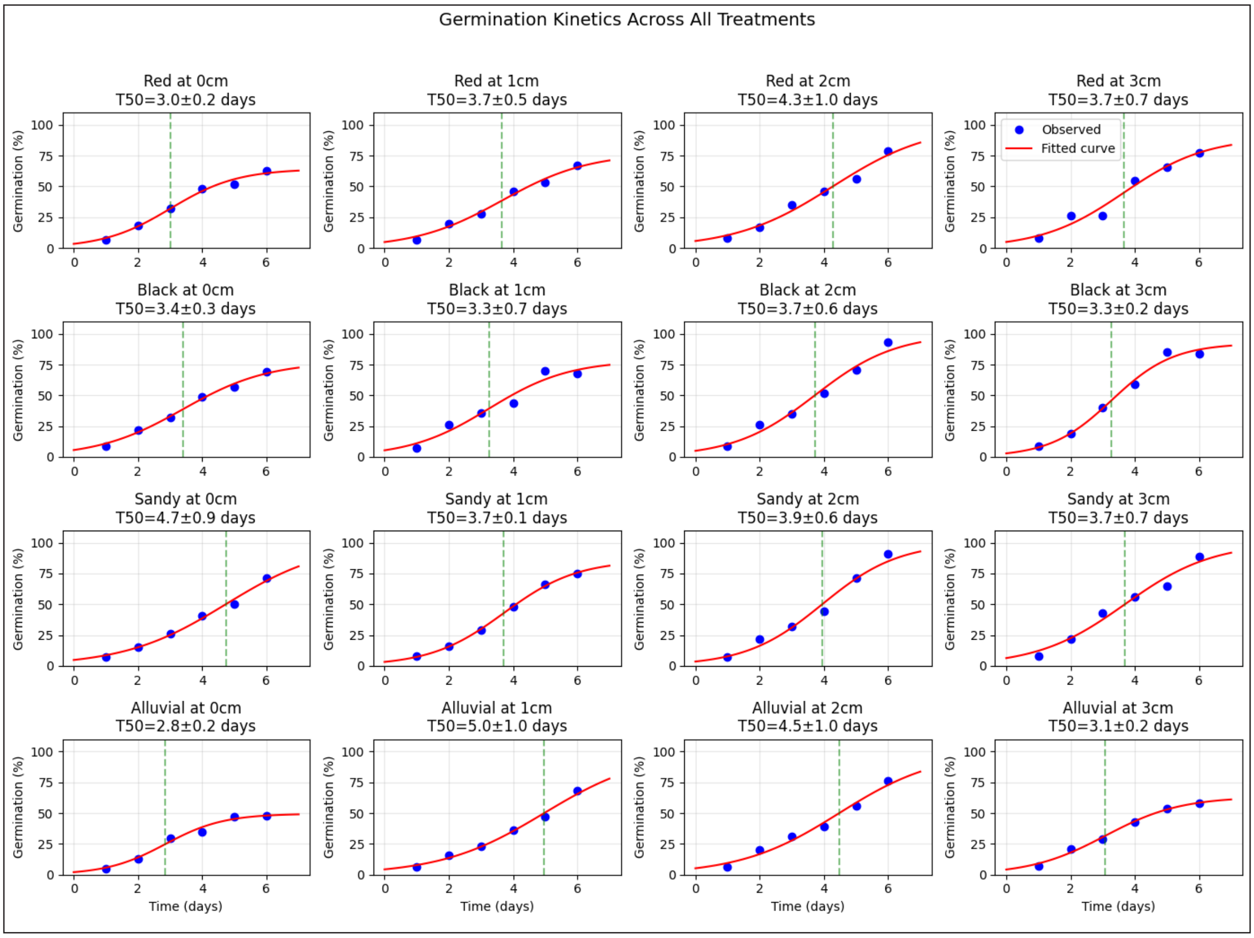

Fig. 1. Germination kinetics curves of Coriandrum sativum L. under different soil types and sowing depths

limited replication or variability in experimental conditions.

To further understand germination dynamics, a logistic growth model was fitted to the germination data (Fig. 1), showing a high goodness-of-fit ($R^2 > 0.90$) across treatments, indicating the model's robustness. The predicted maximum germination percentage (GPmax) showed clear treatment effects. In sandy soil, GPmax reached 100% at 1 to 3 cm depths but was slightly lower at 0 cm (85.9%). In alluvial soil, depth sensitivity was evident: GPmax ranged from 49.5% at 0 cm to 100% at 1 and 2 cm. Black soil showed consistent GPmax across all depths, remaining above 77%.

The estimated germination rate constant (k) and time to 50% germination (T50) also varied with depth and soil type (Fig. 2 and 3). Interestingly, alluvial soil at 0 cm had the fastest germination rate ($k = 1.10$ day^{-1}) and shortest T50 (2.85 days), likely due to immediate moisture availability at the surface, although this did not translate to high final germination. In contrast, sandy soil at 0 cm recorded the lowest germination rate ($k = 0.63$ day^{-1}) and longest T50 (4.73 days), possibly due to surface desiccation. Notably, black soil exhibited increasing germination rates with depth, from 0.75 day^{-1} at 0 cm to 1.04 day^{-1} at 3 cm, further reinforcing its superior performance under deeper sowing conditions.

Vegetative development, as indicated by leaf number, progressed steadily over time in all treatments, as shown in Fig. 4. However, the rate of leaf emergence was influenced by both soil type and depth. Treatments with black and red soils at 1 cm depth showed faster and more uniform leaf development, likely due to earlier and more synchronized germination. In contrast, alluvial soil at 3 cm depth, which had low germination and delayed emergence, showed reduced leaf numbers throughout the observation period. This highlights the long-term effects of early germination success on subsequent vegetative growth stages.

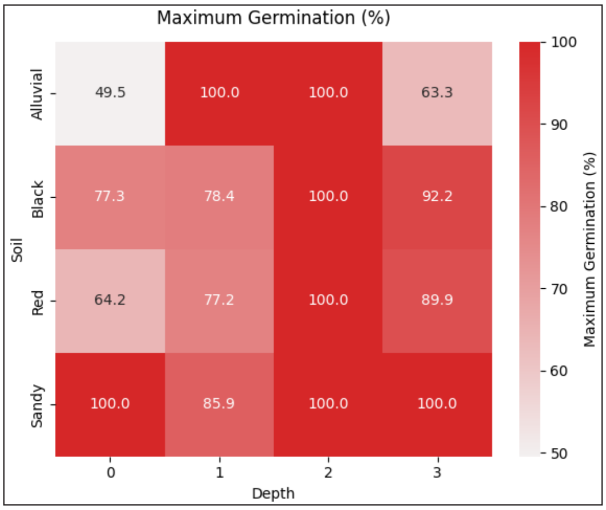

Fig. 2. Heatmaps representing the effects of soil type and sowing depth on maximum germination (%), growth rate (k), and T_{50} (days) of Coriandrum sativum L.

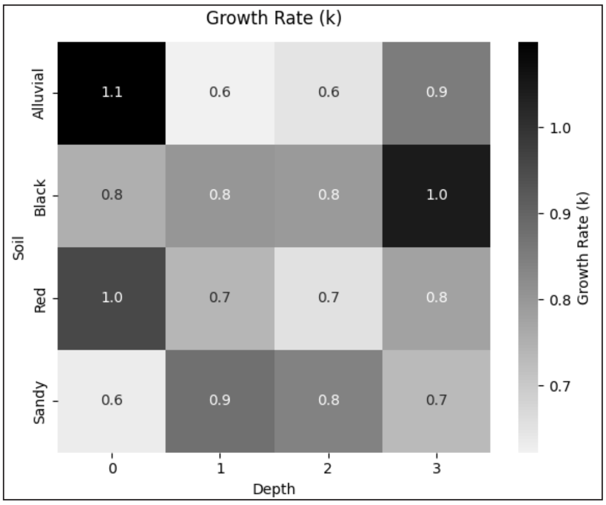

Fig. 3. Heatmaps representing the effects of soil type and sowing depth on growth rate (k) of Coriandrum sativum L.

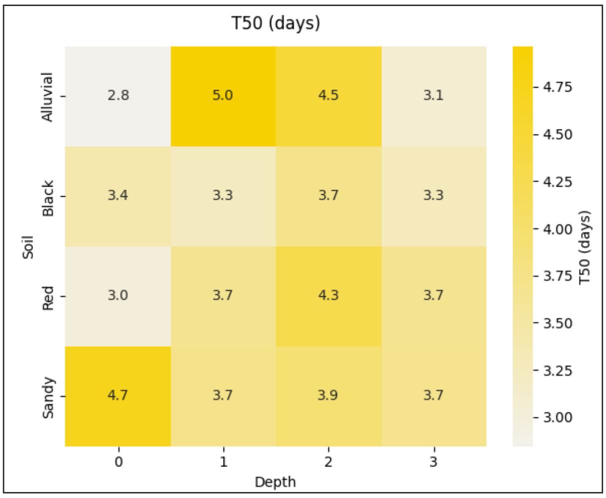

Fig. 4. Heatmaps representing the effects of soil type and sowing depth on T_{50} (days) of Coriandrum sativum L.

Following the assessment of germination parameters, the effect of soil type and sowing depth on early vegetative growth was evaluated by monitoring the number of leaves produced over a six-week period. This served as an important physiological indicator to understand post-germination establishment dynamics under varying edaphic conditions.

By the sixth week, clear differences emerged in leaf production across treatments. At 0 cm sowing depth, sandy soil recorded the highest number of leaves (8.22±1.56), followed by alluvial soil (7.14±1.95), while black (6.11±1.61) and red soils (5.25±1.03) showed lower values. At 1 cm depth, black soil supported the highest leaf count (7±1.30) by sixth week, whereas red, sandy, and alluvial soils exhibited similar outcomes, indicating that moderate sowing depth in nutrient-rich black soil promotes better shoot development.

At 2 cm depth, black soil again facilitated higher leaf development (8±1.65), closely followed by sandy (7.88±1.61) and alluvial soils (7.4±1.14), while red soil remained sub-optimal (5.44±1.23). Interestingly, at 3 cm, sandy soil exhibited the maximum leaf count (11.25±4.03), followed by alluvial (9.5±0.70) and red soil (7±1.85). Contrary to its performance at moderate depths, black soil showed the lowest leaf number at 3 cm (6.9±0.87), suggesting an adverse response to deeper placement possibly due to increased compaction and reduced oxygen diffusion.

The Two-Way ANOVA results indicated that in the first week, neither sowing depth ($p = 0.835$) nor soil type ($p = 0.093$) significantly influenced leaf number, implying that initial leaf emergence is predominantly under genetic control, independent of soil environment. However, in the second week, soil type showed a statistically significant effect ($p = 0.0458$) and sowing depth approached significance ($p = 0.0818$). This indicates that external conditions begin to influence growth patterns as plants transition from germination to active vegetative stages.

By the third week, soil type continued to significantly affect leaf development ($p = 0.048$), while sowing depth approached a more robust level of significance ($p = 0.068$). These results suggest that soil texture, structure, and moisture-holding capacity begin to exert

Table 2. Number of leaves in coriander plants under different soil types and sowing depths

Sowing depth	Soil	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
0 cm	Red	2±0.1	3.28±0.48	3.5±0.53	4±0.53	4.5±0.53	5.25±1.03
	Black	2.28±0.48	3.71±0.48	4.42±0.53	4.87±0.83	5.22±0.97	6.11±1.61
	Sandy	2.57±0.78	3.88±0.78	4.66±0.86	5.22±0.97	5.88±0.92	8.22±1.56
	Alluvial	2±0.81	2.57±1.71	4.16±0.98	5.33±1.50	5.71±1.49	7.14±1.95
1 cm	Red	2.1±0.73	2.7±0.82	3.3±0.82	4.11±0.78	5.4±1.26	6.3±1.05
	Black	2.6±0.51	3.5±0.53	4.25±0.46	5.25±0.46	6±0.75	7±1.30
	Sandy	1.77±0.44	3±0.5	3.7±0.82	4.37±0.91	5.9±1.91	6.8±1.81
	Alluvial	2±0.57	2.83±0.40	3.57±0.78	4.57±0.78	6.57±2.37	7.71±2.28
2 cm	Red	2.37±0.74	2.87±0.35	3.5±0.53	4.25±0.70	4.28±1.36	5.44±1.23
	Black	2.75±0.72	3.22±0.83	4.22±0.83	4.77±1.30	6.77±2.22	8±1.65
	Sandy	2±0.1	3.22±0.66	4±0.70	5.11±0.78	7±1	7.88±1.61
	Alluvial	2±0.1	2.4±0.54	3.4±0.54	4.6±0.89	6±0.70	7.4±1.14
3 cm	Red	2.42±0.53	3.5±0.83	4.37±0.51	5.12±0.64	5.5±1.06	7±1.85
	Black	2.33±0.5	3.66±0.5	4.1±0.87	4.6±1.17	5.6±1.07	6.9±0.87
	Sandy	2±0.1	3.25±0.5	4.5±0.57	5.25±0.5	7.25±1.89	11.25±4.03
	Alluvial	2±0.1	3.5±0.70	4±0	5±0	6.5±0.70	9.5±0.70

greater influence on shoot development during early growth, which corroborates earlier findings on coriander's sensitivity to edaphic variations. Though sowing depth still did not reach conventional significance, the persistent near-significant p-values suggest a minor but potentially influential role, especially in interaction with soil properties.

During the fourth week, no significant effects were found for either factor (depth: $p = 0.5184$; soil type: $p = 0.2142$), implying a temporary equilibrium phase where internal plant factors may override environmental differences. Notably, by weeks five and six, soil type had a statistically significant effect on leaf number ($p = 0.0148$ and $p = 0.0244$, respectively), indicating that accumulated environmental influences increasingly determine vegetative output over time. In contrast, sowing depth remained marginally non-significant, highlighting its declining role in later stages of plant establishment.

Duncan's Multiple Range Test (DMRT) did not reveal any statistically significant pairwise differences between individual treatments, implying that while the overall effect of soil type was clear, it was distributed across multiple combinations rather than concentrated in specific pairings. This broader distribution may reflect the complex interaction between soil texture, porosity, and nutrient dynamics, which collectively modulate early growth responses.

Overall, sandy soil consistently supported higher leaf development, particularly at greater sowing depths, likely due to its superior drainage and reduced resistance to shoot elongation. Conversely, black and red soils performed better at 1-2 cm depths, where moisture retention and compaction levels appear optimal for early vegetative growth. These results collectively suggest that soil type is a more critical determinant of coriander leaf development than sowing depth, especially from the second week onward, while sowing depth plays a secondary and largely transient role. The temporal progression in ANOVA significance supports the notion that plant development transitions from genetic control to edaphic responsiveness, particularly in arid and semi-arid environments where soil characteristics greatly influence establishment success.

In addition to germination percentage, the seedling height of coriander exhibited discernible variations across soil types and sowing depths during the six-week observational period (Table 3). While all treatments displayed a progressive increase in height over time, the magnitude of growth differed based on both soil and depth.

By the sixth week, at 0 cm sowing depth, seedlings in alluvial soil achieved the tallest height (6.65±3.17 cm), followed closely by sandy (6.41±1.76 cm), red (6.1±0.77 cm), and black soil (5.82±1.97 cm). Conversely, at 1 cm

Table 3. Seedling height in coriander plants under different soil types and sowing depths

Sowing depth	Soil	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
0 cm	Red	3.48±0.41	4.4±0.38	4.98±0.40	5.18±0.39	5.6±0.74	6.1±0.77
	Black	3.43±0.90	3.84±0.69	4.35±1.04	4.57±0.79	4.74±0.69	5.82±1.97
	Sandy	3.5±0.76	3.51±0.95	3.92±0.95	2.95±0.73	3.97±0.70	6.41±1.76
	Alluvial	3.1±0.71	3.11±0.74	3.51±0.93	3.98±1.10	4.5±1	6.65±3.17
1 cm	Red	6.28±2.30	6.83±2.44	6.5±1.71	7.46±2.06	7.74±1.79	8.59±2.58
	Black	7.96±1.37	8.1±1.22	7.47±1.11	8.78±1.06	10.63±1.31	12.11±4.13
	Sandy	7.3±1.10	7.71±0.99	6.78±1.97	7.39±1.93	9.19±3.12	10.98±4.61
	Alluvial	7.14±2.57	8.03±2.74	7.84±2.30	7.75±2.66	10.04±3.13	11.28±4.22
2 cm	Red	4.18±0.86	4.48±0.79	4.76±0.70	4.75±0.76	4.53±0.86	5.42±1.65
	Black	4.93±1.27	5.56±1.55	5.72±1.53	6.04±1.64	7.6±1.38	8.63±3.06
	Sandy	5.27±1.68	5.21±2.30	5.62±2.27	6.03±2.24	8.32±3.26	10.53±4.1
	Alluvial	1.73±0.87	2.56±0.66	2.92±0.38	3.78±0.92	6.96±1.59	8.98±2.56
3 cm	Red	4.52±1.99	4.48±1.87	3.72±2.16	4.36±2.06	5.57±2.40	6.66±3.49
	Black	4.07±1.09	4.64±1.07	5.6±1.55	4.63±1.86	5.29±2.19	7.97±2.77
	Sandy	3.6±0.70	5.15±1.24	5.8±1.72	4.95±1.25	7.62±1.94	10.3±3.08
	Alluvial	2.6±0.00	3.7±0.14	4±0.00	2.74±0.07	4.4±0.28	8.3±0.56

depth, black soil supported the highest seedling height (12.11±4.13 cm), outperforming alluvial (11.28±4.22 cm), sandy (10.98±4.61 cm), and red soil (8.59±2.58 cm). Sandy soil, when sown at 2 cm and 3 cm depths, consistently recorded the highest growth-10.53±4.1 cm and 10.3±3.08 cm, respectively-indicating its suitability for deeper sowing. In contrast, red soil consistently yielded the shortest seedlings across depths.

The two-way ANOVA revealed that sowing depth exerted a highly significant influence ($p < 0.001$) on seedling height throughout the study period, affirming its role as a major determinant in early seedling development. Meanwhile, soil type emerged as significant only in week 6 ($p = 0.021$), suggesting that as seedlings matured, edaphic factors such as nutrient availability and soil texture began to play a more prominent role in shoot elongation. However, Duncan's Multiple Range Test (DMT) did not detect significant pairwise differences between specific soil-depth combinations, implying that although general trends were evident, no single treatment was statistically superior.

Complementing the trends observed in height, the seedling stem diameter also varied as a function of soil type and sowing depth over the six-week period (Table 4). A general upward trend was observed in all treatments, albeit with treatment-specific differences in growth rate.

At 0 cm depth, stem diameters plateaued around 0.10 to 0.11 cm by week 6 across all soils, with red, black, and alluvial soils yielding the highest values (0.11±0.01 cm), while sandy soil lagged slightly (0.10±0.01 cm). At 1 cm depth, black soil produced the maximum stem diameter (0.12±0.01 cm), whereas red soil remained the lowest (0.10±0.02 cm). At 2 cm, the trend reversed, with red soil producing the widest stems (0.12±0.03 cm), and alluvial soil the narrowest (0.09±0.01 cm). Interestingly, at 3 cm depth, all three soil types-sandy, black, and alluvial-achieved comparably high diameters (0.12±0.01 cm), indicating favorable conditions for late-stage stem thickening.

Statistical analysis via two-way ANOVA showed that sowing depth significantly influenced stem diameter in the initial week ($p = 0.0233$), highlighting its critical role during early establishment. By week 2, soil type became a significant factor ($p = 0.0326$), reflecting its growing importance in nutrient-mediated development. During Weeks 3 and 4, neither factor exerted statistically significant effects ($p > 0.24$ and $p > 0.77$, respectively), suggesting a period of relative physiological stability across treatments. However, by Week 5, soil type regained significance ($p = 0.0343$), and sowing depth approached significance ($p = 0.0628$). By the sixth week, both factors were statistically significant (depth: $p = 0.0016$; soil: $p = 0.0216$), affirming that while early

Table 4. Seedling stem diameter in coriander plants under different soil types and sowing depths

Sowing depth	Soil	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
0 cm	Red	0.06±0.02	0.07±0.01	0.09±0.01	0.1±0.01	0.11±0.01	0.11±0.01
	Black	0.07±0.01	0.09±0.01	0.1±0.02	0.09±0.03	0.1±0.01	0.11±0.01
	Sandy	0.06±0.01	0.1±0.007	0.09±0.009	0.07±0.01	0.1±0.01	0.1±0.01
	Alluvial	0.06±0.02	0.09±0.01	0.1±0.01	0.09±0.01	0.1±0.02	0.11±0.02
1 cm	Red	0.06±0.02	0.06±0.005	0.08±0.01	0.09±0.02	0.1±0.02	0.1±0.02
	Black	0.07±0.03	0.1±0.007	0.09±0.006	0.11±0.007	0.11±0.008	0.12±0.01
	Sandy	0.07±0.01	0.1±0.005	0.09±0.005	0.08±0.01	0.09±0.01	0.1±0.007
	Alluvial	0.08±0.01	0.08±0.009	0.09±0.01	0.09±0.01	0.09±0.01	0.1±0.01
2 cm	Red	0.08±0.01	0.08±0.01	0.09±0.01	0.1±0.02	0.11±0.03	0.12±0.03
	Black	0.09±0.02	0.08±0.008	0.1±0.007	0.11±0.01	0.12±0.01	0.11±0.02
	Sandy	0.07±0.01	0.09±0.01	0.1±0.005	0.21±0.33	0.11±0.03	0.11±0.03
	Alluvial	0.07±0.01	0.09±0.008	0.1±0.007	0.1±0.007	0.1±0.008	0.09±0.01
3 cm	Red	0.1±0.02	0.09±0.02	0.11±0.01	0.11±0.01	0.11±0.01	0.11±0.01
	Black	0.09±0.02	0.09±0.01	0.09±0.01	0.11±0.01	0.1±0.01	0.12±0.01
	Sandy	0.1±0.02	0.11±0.008	0.11±0.005	0.12±0.01	0.1±0.01	0.12±0.01
	Alluvial	0.07±0.02	0.08±0.04	0.08±0.03	0.12±0.01	0.09±0.007	0.12±0.007

growth was depth-driven, soil properties gained dominance in later stages.

Despite these significant trends, DMT analyses failed to identify statistically significant pairwise differences at any time point, indicating relatively high within-treatment variability. Nonetheless, certain patterns were discernible: black soil at 1 cm and sandy soil at 3 cm were favorable combinations for achieving thicker stems, underscoring their respective strengths in early and later-stage structural development.

These findings collectively emphasize that while sowing depth is pivotal during the early growth phases, soil type becomes increasingly decisive as coriander seedlings mature. Both parameters interactively influence plant morphology, and strategic optimization of these agronomic factors could substantially enhance early vigour and uniform stand establishment in coriander cultivation.

Further insight into the interrelationships among sowing conditions, germination traits, and early vegetative growth was obtained through correlation analysis (Table 5). A moderate negative correlation was observed between germination percentage (GP) and both sowing depth (r = -0.39) and soil type (r = -0.55), indicating that shallower sowing and soils with specific textural properties-particularly black soil, which was coded

Table 5. Correlation matrix of sowing, germination, and growth parameters

	Sowing depth	Soil type	GP	MGT	GI	GS	PV	CVG	NL Week 6	SH Week 6	SD Week 6
Sowing depth	1										
Soil type	0	1									
GP	-0.39	-0.55	1								
MGT	0.51	0.39	-0.54	1							
GI	-0.46	-0.38	0.58	-0.89	1						
GS	-0.44	-0.46	0.69	-0.86	0.98	1					
PV	-0.28	-0.38	0.34	-0.69	0.88	0.84	1				
CVG	-0.38	-0.3	0.33	-0.86	0.94	0.88	0.93	1			
NL Week 6	0.48	0.57	-0.63	0.4	-0.47	-0.51	-0.31	-0.3	1		
SH Week 6	0.21	0.39	-0.1	-0.04	0.15	0.13	0.35	0.27	0.42	1	
SD Week 6	0.4	-0.28	-0.2	-0.18	0.11	0.04	0.19	0.18	0.18	-0.09	1

Germination percentage (GP), Mean germination time (MGT), Germination speed (GS), Germination index (GI), Peak value (PV), Coefficient of velocity of germination (CVG), number of leaves (NL), seedling height (SH), seedling diameter (SD) with lower numerical values-favored higher germination success. This is in agreement with prior physiological findings suggesting that shallow sowing promotes improved oxygen availability and reduces mechanical resistance, thereby facilitating seedling emergence (Bewley *et al.*, 2013).

Among germination traits, a strong inverse relationship was detected between mean germination time (MGT) and germination index (GI) (r = -0.89), highlighting that rapidly germinating seeds exhibited greater vigour. Moreover, germination speed (GS) was found to be highly correlated with GI (r = 0.98), indicating that both parameters are robust indicators of overall germination efficiency. This observation is further corroborated by the positive correlations of peak value (PV) and coefficient of velocity of germination (CVG) with GI (r = 0.88 and r = 0.94, respectively), suggesting that these metrics collectively describe the early performance and synchrony of germinating seeds.

Interestingly, the analysis also unveiled potential trade-offs between early germination success and subsequent vegetative development. Specifically, the number of leaves at week 6 (NL Week 6) showed a negative correlation with GP (r = -0.63), suggesting that seeds which germinated rapidly might have allocated resources differently, possibly limiting later vegetative development. This is indicative of a growth-defence trade-off, wherein early rapid development may come at the cost of sustained vegetative expansion. Conversely, a positive correlation between NL Week 6 and sowing depth (r = 0.48) indicates that deeper-sown seeds, although slower to germinate, may benefit from enhanced root anchorage or prolonged soil moisture access, enabling more robust leaf development during later growth stages.

The influence of soil type on vegetative metrics further supports this trade-off hypothesis. Although soil type correlated negatively with GP (r = -0.55), it showed a positive correlation with NL Week 6 (r = 0.57). This duality suggests that black soil, despite sometimes showing slower or reduced germination under specific sowing depths, provides a superior edaphic environment for seedling establishment and sustained vegetative growth, likely due to its favorable nutrient-holding and water-retention properties. On the other hand, sandy soils, while promoting faster initial germination due to enhanced aeration and low compaction, may fail to support long-term seedling growth because of poor moisture and nutrient availability.

Taken together, these correlation patterns underscore the complex interplay between sowing depth, soil physical properties, and germination behaviour, and how these early-phase processes influence downstream vegetative development. While high germination percentages are desirable, the physiological timing and synchrony of emergence, as well as the resource environment, ultimately govern seedling establishment success and early biomass accumulation. These findings have practical implications for optimizing coriander sowing strategies in variable soil conditions.

For established plants to maintain a positive yield, high seedling germination and growth are essential. Understanding the appropriate sowing depth is therefore crucial for achieving optimal stand density and overall crop performance (Grace and Mbogue, 2020). The results of the present study indicate that *Coriandrum sativum* seeds exhibited a significantly lower germination percentage when sown at greater depths. Thiyam *et al.* (2017) further noted that smaller seeds of peas (*Pisum sativum*), perform better at shallow sowing depths, while Sime *et al.* (2020) found that maize (*Zea mays*) germination was optimal at an intermediate sowing depth of 6 cm compared to shallower (2 cm) or deeper (10 cm) depths.

Conclusions

This study clearly demonstrates that both sowing depth and soil type significantly influence the germination, early vegetative growth, and seedling development of *Coriandrum sativum*. Among all treatments, a sowing depth of 1 cm in black and red soils emerged as the most effective strategy for achieving high germination percentage, rapid emergence, and uniform seedling establishment. While black soil consistently supported superior performance across traits due to its favorable moisture retention and nutrient availability, sandy soils showed improved vegetative development at deeper sowing (2-3 cm), particularly in terms of leaf number and shoot height. Statistical analysis and logistic modelling further revealed that although sowing depth primarily affected early germination kinetics, soil type had a more sustained influence on vegetative traits over time. Correlation analyses indicated a trade-off between early germination vigour and later vegetative growth, underscoring the need to balance emergence timing with long-term seedling robustness. Overall, the findings suggest that tailored sowing strategies, incorporating moderate depth placement (1-2 cm) in soil-specific contexts, can substantially enhance stand establishment and crop performance in coriander.

Statements

Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

All data generated and analysed during this study are fully included in the manuscript. No additional datasets were created or used.

Author Contributions

RM, KNO, and JB designed and conducted the experiments. BAJ supervised the research and provided critical revisions. Data collection and analysis were performed by RM and KNO. The manuscript was written and reviewed by all authors, who approved the final version.

AI Assistance Statement

AI assistance was used solely for language enhancement, grammar refinement, and improving the readability of the manuscript. No AI-generated content was included in the research design, data analysis, or interpretation of results.

Acknowledgments

The authors sincerely acknowledge the guidance and support of Dr. N.K. Odedra and Dr. A.R. Modhvadia, Associate Professors, Department of Botany, M.D. Science College, Porbandar, for their valuable insights and encouragement throughout this study.

References

Al-Mudaris, M. 1998. Notes on various parameters recording the speed of seed germination. *Der Tropenlandwirt* 99: 147-154.

Anonymous. 2022. Global data of rank, production and production share of coriander in major countries. Retrieved from www.tridge.com on 23 June, 2024.

Bewley, J.D., Bradford, K.J., Hilhorst, H.W. and Nonogaki, H. 2013. Seeds: Physiology of Development, Germination and Dormancy. Springer. https://doi.org/10.1007/978 1-4614-4693-4

Czabator, F.J. 1962. Germination value: An index combining speed and completeness of pine seed germination. *Forest Science* 8(4): 386-396.

Evetts, L.L. and Burnside, O.C. 1972. Germination and seedling development of common milkweed and other species. *Weed Science* 20(4): 371-378. https://doi.org/10.1017/S004317450003589X

Gowtham, T. and Mohanalakshmi, M. 2018. Influence of growing environment on growth and yield parameters of coriander under shade net and open field condition. *Madras Agricultural Journal* 105(7-9): 332-335. https://doi.org/10.29321/MAJ.2018.000155

Grace, A.M. and Mbogue, C.N.N. 2020. Effects of sowing depth on seed germination and seedling growth of *Aframomum citratum* (Pereira) K. Schum. *African Journal of Plant Science* 14(7): 262-269. https://doi.org/10.5897/AJPS2018.1728

Maguire, J.D. 1962. Speed of germination-Aid in selection and evaluation for seedling emergence and vigor. *Crop Science* 2(2): 176-177. https://doi.org/10.2135/cropsci1962.0011183X000200020033x

Martínez, M.L., Valverde, T. and Moreno-Casasola, P. 1992. Germination response to temperature, salinity, light and depth of sowing of ten tropical dune species. *Oecologia* 92: 343-353. https://doi.org/10.1007/BF00317460

Prasad, S. 2024. Genetic components for germination indices, root architecture and their correlation with field emergence of cowpea varieties. *Journal of Eco-Friendly Agriculture* 19(2), 324-328. https://doi.org/10.48165/jefa.2024.19.02.15

Santhosh, N., Shankar, R., Narendranath, R. and Srinivasan, K. 2019. Research of production and growth of coriander in various seasons using K-means algorithm. International *Journal of Innovative Technology and Exploring Engineering* 8: 518-521. https://doi.org/10.35940/ijitee.L1129.10812S19

Shafii, B. and Price, J. 2001. Estimation of cardinal temperatures in germination data analysis. *Journal of Agricultural, Biological and Environmental Statistics* 6: 356-366. https://doi.org/10.1198/108571101317096569

Sime, B., Mekuria, M. and Getachew, E. 2020. Effect of different sowing depth on germination and growth performance of maize (*Zea mays* L.) at Jimma, Southwest Ethiopia. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3571331

Stat Ledger 2024. India coriander seed market: Trend analysis & forecast to 2030 (Vijayapur, Karnataka, 145 pp.). Retrieved from https://statledger.com/products/india-coriander-seed-market-trend-analysis-forecast-to-2030?variant=45718468034798

Thiyam, R., Yadav, B. and Rai, P.K. 2017. Effect of seed size and sowing depth on seedling emergence and seed yield of pea (*Pisum sativum*). *Journal of Pharmacognosy and Phytochemistry* 6(4): 1003-1005.

Printed in September 2025