



RESEARCH ARTICLE

Yield potential and comparative performance of coriander (*Coriandrum sativum* L.) genotypes under hydroponic and geoponic systems for off-season cultivation

Vansangkimi¹, Parveen Sharma^{1*}, Payal Sharma^{1*}, Arshia Prashar¹, Shorya Kapoor¹, Abhishek Kumar² & Himanshu Thakur³

¹Department of Vegetable Science and Floriculture, College of Agriculture, Chaudhary Sarwan Kumar (CSK) Himachal Pradesh Krishi Vishvavidyalaya, Palampur 176 062, Himachal Pradesh, India

²Department of Biotechnology, Graphic Era, (Deemed to be University), Dehradun 248 002, Uttarakhand, India

³Department of Entomology, College of Agriculture, Chaudhary Sarwan Kumar (CSK) Himachal Pradesh Krishi Vishvavidyalaya, Palampur 176 062, Himachal Pradesh, India

*Correspondence email - payalsharma472@gmail.com; parveens012@gmail.com

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Abstract

A total of 21 genotypes of coriander were investigated under soil (geoponic) and soilless (hydroponic: nutrient film technique) environments, for estimating variation, association and path analysis for different yield related attributes. The study was first of its kind in comparing hydroponic and soil culture and observations revealed that the hydroponic growing system outperformed the geoponic system for yield as well as for most of the important yield attributing characters. Markedly wide ranges in both phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) were noted for attributes such as leaf number, branch number/plant, leaf area and canopy spread, reflecting ample genetic variability in the material studied. Likewise, these traits along with dry matter content and yield/plant showed high heritability further being accompanied by substantial genetic gain, implying that additive genetic effects predominate and improvement through straight forward selection would be highly successful. Yield/plant expressed significantly positive correlation with number of leaves/plants, number of branches/plants, petiole length, leaf area, root length, plant spread, plant height, number of cuttings and chlorophyll content. Path analysis showed that leaf number, branch production, leaf surface area, overall plant spread, cutting ability and chlorophyll level all contributed directly and positively to yield/plant at both the scales. Their consistent influence suggests that these traits serve as strong indicators for selecting high-yielding coriander lines.

Keywords: coriander; hydroponic; nutrient film technique; polyhouse; yield

Introduction

Coriander (*Coriandrum sativum* L.; 2n=22) (Family: Apiaceae) a fast-growing annual spice and aromatic plant, also known as Chinese parsley or cilantro, is valued for its versatile use in the culinary world (1, 2). The plant was originated in Mediterranean region (3, 4). Depending on the climatic conditions, it can be grown as a summer or winter annual. The total coriander production in India during 2022–23 was 847000 metric tons covering an area of 638000 ha (5, 6). In Northern India, coriander is typically a rabi (winter) crop. However, there is a high demand for its green leaves during spring and summer, when the supply is limited. Consequently, growing coriander in the summer (off-season) can provide additional income for farmers (7, 8). Protected cultivation technologies such as greenhouse cultivation and hydroponic technology can be encouraged to achieve maximum herbage yield year-round (9). The main advantage of hydroponic systems lies in their efficient use of resources, particularly water and growing

space (10). Hydroponics has the benefits of preventing crop loss due to attacks by soil-borne pests and salinity (11). Results from several studies have confirmed that hydroponics outperforms conventional soil-based systems in terms of increased yield per area, greater planting density and improved efficient use of inputs (3, 12, 13). The higher yield obtained through hydroponics is due to the controlled climatic conditions, which allows for continuous crop production all year round (14). Hydroponic cultivation is highly suitable for leafy coriander as it ensures precise nutrient and water supply, promoting rapid and uniform vegetative growth (2, 3). The shallow root system of coriander efficiently absorbs nutrients in soilless conditions, leading to greater leaf biomass. Stable growth conditions support quick regrowth after harvest, enabling multiple cuttings. Soil-free production improves leaf cleanliness and reduces pest and disease incidence. Additionally, controlled environments help delay bolting, maintaining

tenderness and higher leaf yield (6, 7). Conventional agriculture that is based on soil cultivation places a strain on the planet's natural resources as it demands significant amounts of land and water (15). The widespread use of pesticides and fertilisers in soil-based farming contributes to different environmental problems such as soil deterioration, increased greenhouse gas emissions and groundwater contamination (1, 16, 17). Hydroponics can be a practical solution to improve agricultural production, ensuring a stable food supply chain. In regards to crop improvement in coriander for leafy purpose, developing genotypes with high leaf yield is an important breeding goal. An effective breeding program relies on assessing the extent and nature of variability within germplasm to identify superior lines possessing desirable yield and quality traits, ultimately enabling the development of high-yielding varieties. Therefore, evaluation and identification of coriander cultivars suitable for production under hydroponics and protected environments should be performed as there was no such study conducted so far where coriander plants have been accessed in hydroponic systems. In view of recent advancements, the current study was undertaken to assess the performance of 20 coriander accessions along with one local check variety and to assess genetic components of variation, trait associations and path coefficients for yield-related characteristics. Although the work has been done in coriander but not much in the aspect of leafy coriander in hydroponic system [nutrient film technique (NFT) system] and naturally ventilated polyhouses. The comparative study has not been done yet in leafy coriander for both the system. Therefore, the study has been designed in such a way to cover broad spectrum of leafy coriander growth and their yield potential in both hydroponic system and naturally ventilated polyhouses.

Material and Methods

Experimental materials

The research was investigated at Vegetable farm Chaudhary Sarwan Kumar (CSK) Himachal Pradesh Krishi Vishvavidyalaya (CSK HPKV), Palampur, Himachal Pradesh, India. A total of 20 accessions were sourced from ICAR-National Research Centre on Seed Spices, Tabiji, Ajmer (Rajasthan) along with one local check i.e., Sangla Local for experimental material. The various accessions with the source have been mentioned in Table 1.

Experimental layout

The experimental material, comprising 21 coriander genotypes, was evaluated for different yield related traits by following completely randomized design (CRD) consisting of 3 replications in both a naturally ventilated polyhouse and a hydroponic system (NFT system). The treatments were randomly allocated to each experimental unit. In each replication, 5 plants of each line/genotype were tagged randomly which were further used for recording data. In protected and hydroponic cultivation, growth-related measurements are generally recorded during the active vegetative phase prior to harvest, whereas yield parameters are assessed at the time of cutting or harvest.

Fertilisers application and fertigation

Within the hydroponic setup, crop growth was supported using a Hoagland-based nutrient mix and the fertigation process was adjusted according to fluctuations in the nutrient solution's electrical conductivity (EC) and pH levels. The values of electrical conductivity and pH during the cropping period were maintained for optimal growth and development of coriander. The EC ranged from 1.4–1.8 mS/cm and pH range was 6.0–7.0. In polyhouse, farmyard manure (FYM) was applied at 5 tons per hectare along with nitrogen, phosphorous and potassium (NPK) (12:32:16) at 50:50:50 kg/ha as basal dose followed by fertigation with water soluble fertiliser (19:19:19) at 2g/m² area. The fertigation started 3 weeks after germination and was done twice a week to maintain healthy plants.

Observations recorded

Observations were recorded in each replication for traits including number of leaves/plant, number of branches/plant, petiole length (cm), leaf area (cm²), root length (cm), plant spread (cm²), days to marketable harvest, dry matter content (%), moisture content (%), yield/plant (g), plant height (cm), number of cuttings, total soluble solids (TSS °Brix), ascorbic acid content (mg 100 g⁻¹), chlorophyll content (mg g⁻¹), leaf colour, stem colour and leaf margin. The final resulted view of coriander under naturally ventilated polyhouse and hydroponic system is shown in Fig. 1.

Statistical analysis

Genetic variability for the studied traits was assessed using the procedure proposed by Burton and De Vane (18). Estimates of heritability and the expected genetic gain were generated according to Johnson et al. (19). Genotypic and phenotypic correlation coefficients were assessed using the methodology described by Al-Jibouri et al. (20), while path coefficient analysis was carried out in accordance with the procedure proposed by Dewey and Lu (21).

Results and Discussion

Under genotypic growing conditions, characters like leaf area, leaf number/plant, branch number/plant and canopy spread exhibited high levels of variability, with both phenotypic coefficient of variation (PCV) and genotypic coefficient of variation (GCV) exceeding 20 % (Table 2). Recorded moderate (10–20 %) for yield/plant, dry matter, total soluble solids (TSS), root length, petiole length, chlorophyll content, ascorbic acid content and plant height, while low (<10 %) for number of cuttings, moisture and days to marketable harvest. As presented in Table 2, the hydroponic experiment showed that leaf area, number of leaves and number of branches/plants recorded the highest levels of PCV and GCV. Moderate variability was observed for traits like plant spread, dry matter percentage, yield/plant, TSS, chlorophyll concentration, petiole length and number of cuttings. Conversely, traits such as root length, plant height, ascorbic acid content, days to reach marketable stage and moisture content exhibited only low PCV and GCV values. The estimates of heritability (broad

Table 1. List of coriander (*Coriandrum sativum*) accessions used in the study

Sl. No.	Source	Genotype
1	Warangal, Telangana	IC-398747, IC-570280
2	Lam, Guntur Andra Pradesh	LCC-46, LCC-74, LCC-91, LCC-116, LCC-123, LCC-136, LCC-139, LCC-160, LCC-188, LCC-206, LCC-229
3	Jobner, Rajasthan	UD-48, UD-62, UD-118, UD-523, UD-643, UD-714, UD-759
4	Sangla, Himachal Pradesh	Sangla Local (C)

Table 2. Estimates of parameters of variability for various traits in coriander under geponic and hydroponic system

Traits	Range		GCV (%)		PCV (%)		h^2_{bs}		GA (%)	
	Geponic	Hydroponic	Geponic	Hydroponic	Geponic	Hydroponic	Geponic	Hydroponic	Geponic	Hydroponic
No. of leaves per plant	13.26-35.88	20.41-40.23	32.72	23.08	32.92	23.44	98.82	96.95	67.01	46.81
No. of branches per plant	5.23-14.36	8.35-17.48	28.26	21.22	28.46	21.35	98.62	98.75	57.81	43.43
Petiole length (cm)	3.70-5.71	3.81-5.84	13.07	11.55	13.27	11.76	97.04	96.48	26.53	23.38
Leaf area (cm ²)	50.20-184.85	55.44-221.09	43.70	36.39	43.89	36.64	99.15	98.65	89.64	74.45
Root length (cm)	11.34-19.50	14.53-20.27	13.26	8.86	13.75	9.70	93.06	83.38	26.35	16.67
Plant spread (cm ²)	214.15-633.15	315.26-643.00	26.09	18.68	26.31	19.00	98.35	96.63	53.30	37.82
Days to marketable harvest	23.60-26.60	22.70-26.00	2.78	4.53	4.44	6.12	39.08	54.78	3.58	6.91
Dry matter (%)	8.73-17.73	5.37-17.50	15.10	15.45	15.23	15.55	98.29	98.74	30.84	31.63
Moisture (%)	82.27-91.27	82.50-94.63	4.20	4.24	4.24	4.27	98.29	98.74	8.58	8.68
Yield/plant (g)	3.59-8.20	7.02-12.81	17.05	15.13	17.38	15.47	96.24	95.63	34.46	30.48
Plant height (cm)	28.47-47.47	34.14-51.26	10.78	8.26	11.27	9.08	91.41	82.66	21.23	15.46
No. of cuttings	1.47-2.13	2.00-3.20	7.96	11.11	8.98	11.71	78.68	89.95	14.55	21.70
TSS (°Brix)	4.63-7.53	5.60-8.36	13.62	13.45	14.13	13.81	92.86	94.86	27.03	26.98
Ascorbic acid content (mg/100 g)	71.12-117.56	92.67-123.01	10.93	7.73	11.49	8.53	90.55	82.16	21.42	14.43
Chlorophyll content (mg/g)	1.42-2.57	1.31-2.48	12.24	12.11	12.83	12.75	90.95	90.21	24.04	23.70

PCV: phenotypic coefficient of variation; GCV: genotypic coefficient of variation; h^2_{bs} : heritability in broad sense; GA: genetic advance.

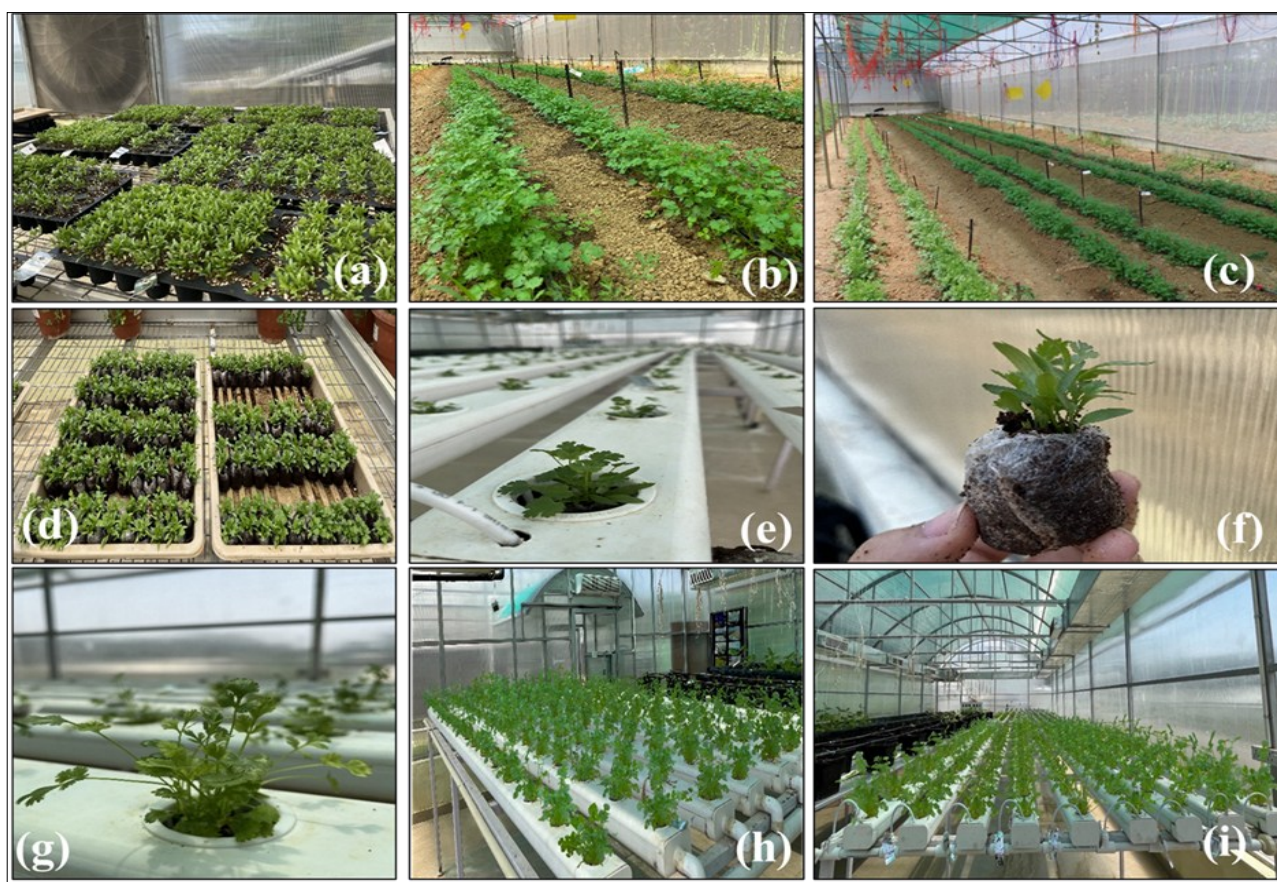


Fig. 1. Coriander under hi-tech nursery, naturally ventilated polyhouse and hydroponic system. (a) hi-tech nursery for geponic polyhouse environment; (b, c) Geponic trial under naturally ventilated polyhouse; (d) hi tech nursery for hydroponic environment; (e) plant under nutrient film technique (NFT) system; (f) plant in cocopeat jiffy supported with plastic net cups; (g) plant representing shoots and (h, i) Hydroponic trial under hi-tech hydroponic nutrient film technique (NFT) system.

sense) in geponic system varied from 39.08–99.15 %. Heritability values above 70 % were obtained for a wide range of traits, including leaf area, leaf and branch numbers per plant, canopy spread, dry matter and moisture levels, petiole length, yield per plant, root length, TSS, plant height, chlorophyll concentration, ascorbic acid content and the number of cuttings, indicating strong genetic control over these characteristics. In contrast, days to marketable harvest exhibited low heritability (<50 %). Broad-sense heritability estimates under the hydroponic system ranged from 54.78–98.75 % (Table 2). The high heritability observed for

these traits indicates minimal environmental influence and a predominant role of genetic factors in determining their expression, suggesting that selection based on the phenotypic performance would be effective. These elevated heritability levels suggest that additive genetic effects largely govern these traits, indicating that they can be effectively improved through selection in upcoming breeding efforts. However, heritability estimates alone may not fully reflect the breeding value of a trait (22). Genetic advance as a percentage of the population means (genetic gain) varied from low to high across the studied traits. In the geponic

system, genetic gain ranged from 3.58–89.64% (Table 2). Genetic advance exceeding 25 % was observed for leaf area, leaf count/plant, branch number/plant, plant spread, per-plant yield and dry matter content, indicating strong potential for improvement through selection. Moderate genetic gain (15–25 %) was observed for TSS, petiole length, root length, chlorophyll content, ascorbic acid content and plant height, while low (<15 %) was noted for number of cuttings, moisture content and days to marketable harvest. Characters such as number of leaves and branches/plant, leaf area, canopy spread, dry matter content and yield/plant exhibited high heritability coupled with considerable genetic advance.

In the hydroponic evaluation, the expected improvement from selection, expressed as genetic advance relative to the population mean, showed substantial variation among the studied characters, with values extending from 6.91–74.45 % (Table 2). The most pronounced genetic gains were recorded for leaf area, number of leaves/plants, number of branches/plants, plant spread, dry matter accumulation and yield/plant, indicating strong potential for improvement through selection. Traits including total soluble solids, chlorophyll content, petiole length, number of cuttings, root length, plant height and ascorbic acid content exhibited moderate levels of genetic gain. Characters such as number of leaves and branches/plant, leaf area, plant spread, dry matter content and yield/plant combined high heritability along with high genetic advance, reflecting a predominant contribution of additive genetic effects. This genetic behaviour suggests that these traits would respond effectively to selection based on phenotypic performance under hydroponic conditions.

The results recorded in the present investigation closely align with earlier observations in coriander, who documented comparable trends in genetic variability across various evaluated attributes (23). Characters such as primary branches, secondary branches and leaf yield/plot exhibited a favourable combination of high heritability and moderate genetic advance expressed as a percentage of the mean. This genetic pattern indicated that these traits are predominantly under additive genetic control and therefore respond efficiently to improvement through direct selection. In contrast, traits including number of leaves per plant (4.73 %) and days to germination (8.47 %) showed limited variability, implying a narrower genetic base; nevertheless, incremental gains through selection cannot be ruled out (23). Further supporting these observations, characters such as number of schizocarps per umbel and umbel diameter were associated with high heritability estimates, whereas seed yield per plant recorded the maximum genetic advance relative to the population mean. Conversely, number of umbellate per umbel expressed the lowest genetic advance (17). Among the yield-related traits, leaf yield an economically important attribute was characterised by high heritability (87 %) accompanied by substantial genetic advance (48.93 %), confirming its reliability and effectiveness as a key selection criteria in coriander breeding programs.

Correlation coefficient studies

Under the geponic system (Table 3), correlation analysis divulged that yield/plant was positively and significantly related to a wide range of vegetative and physiological traits, including plant spread, plant height, number of cuttings, number of branches and leaves/plant, leaf area, root length, petiole length and chlorophyll concentration. The number of leaves/plants expressed strong

positive associations with branching behaviour, leaf area expansion, plant spread, root development, plant stature, number of cuttings, petiole length and chlorophyll content, indicating its central role in overall plant vigour. Likewise, number of branches/plants was positively and significantly correlated with leaf area, plant spread, root length, number of cuttings, plant height, petiole length and chlorophyll concentration, reflecting coordinated growth among these attributes. Petiole length showed significant positive relationships with root length, number of cuttings, plant spread, leaf area, plant height, chlorophyll concentration and moisture content; however, it showed a significant negative association with dry matter accumulation and ascorbic acid content at the genotypic level. Leaf area was positively correlated with plant spread, root length, number of cuttings, plant height and chlorophyll concentration, emphasising its contribution to photosynthetic capacity. Root length also displayed significant positive correlations with plant spread, plant height, number of cuttings and chlorophyll content. Plant spread itself was positively associated with plant height, number of cuttings and chlorophyll concentration, while plant height showed significant positive relationships with number of cuttings and chlorophyll content. In disparity, TSS had a significant negative association with plant height. The number of cuttings was positively correlated with chlorophyll content but showed a significant negative correlation with TSS.

In the hydroponic system (Table 4), genotypic correlation analysis demonstrated that yield per plant was significantly and positively associated with plant height, plant spread, number of cuttings, leaf area, root length, number of branches, number of leaves/plants, petiole length, chlorophyll concentration and days to marketable harvest. Conversely, ascorbic acid content showed a significant negative relationship with yield per plant. The number of leaves/plants exhibited strong positive correlations with number of branches, leaf area, root length, plant spread, number of cuttings, petiole length, plant height, chlorophyll content and days to marketable harvest, while displaying a negative association with ascorbic acid content. Similarly, number of branches per plant showed significant positive relationships with number of cuttings, leaf area, root length, plant spread, plant height, petiole length, chlorophyll concentration and days to marketable harvest, but was negatively correlated with ascorbic acid content. Petiole length was positively associated with leaf area, plant spread, root length, number of cuttings, plant height and chlorophyll content, whereas it exhibited a negative association with ascorbic acid. Leaf area showed significant positive correlations with root length, plant spread, plant height, number of cuttings and chlorophyll content, while maintaining a negative relationship with ascorbic acid content. Root length followed a similar pattern, being positively correlated with plant spread, plant height, number of cuttings and chlorophyll concentration and negatively associated with ascorbic acid. Plant spread was positively correlated with plant height, number of cuttings and chlorophyll content but negatively correlated with ascorbic acid content. Plant height exhibited positive associations with number of cuttings and chlorophyll content, alongside a negative relationship with ascorbic acid. The number of cuttings itself exhibited a positive correlation with chlorophyll content and a negative correlation with ascorbic acid. Additionally, days to marketable harvest displayed a significant positive association with number of cuttings, while chlorophyll content and ascorbic

Table 3. Estimates of genotypic (G) and phenotypic (P) correlation coefficients for different pair of traits in coriander under geponic system

Traits	No. of leaves per plant	No. of branches per plant	Petiole length (cm)	Leaf area (cm ²)	Root length (cm)	Plant spread (cm ²)	Days to market-able harvest	Dry matter (%)	Moisture (%)	Plant height (cm)	No. of cuttings	TSS (° Brix)	Ascorbic acid content (mg/100 g)	Chloro-phyll content (mg/g)
No. of branches per plant	G	0.998**												
	P	0.983**												
Petiole length (cm)	G	0.671**	0.672**											
	P	0.657**	0.654**											
Leaf area (cm ²)	G	0.993**	0.985**	0.680**										
	P	0.987**	0.974**	0.663**										
Root length (cm)	G	0.922**	0.934**	0.745**	0.910**									
	P	0.887**	0.892**	0.701**	0.872**									
Plant spread (cm ²)	G	0.926**	0.945**	0.689**	0.869**									
	P	0.913**	0.932**	0.674**	0.827**									
Days to marketable harvest	G	0.205	0.201	0.084	0.137	0.235								
	P	0.117	0.124	0.019	0.097	0.144								
Dry matter (%)	G	-0.073	-0.075	-0.391**	-0.164	-0.200	0.132							
	P	-0.074	-0.073	-0.381**	-0.159	-0.195	0.074							
Moisture (%)	G	0.073	0.075	0.391**	0.164	0.200	-0.132	-1.000**						
	P	0.074	0.073	0.381**	0.159	0.195	-0.074	-1.000**						
Plant height (cm)	G	0.812**	0.859**	0.592**	0.784**	0.928**	0.245	-0.219	0.219					
	P	0.772**	0.808**	0.556**	0.735**	0.872**	0.113	-0.212	0.212					
No. of cuttings	G	0.819**	0.880**	0.702**	0.875**	0.944**	0.152	-0.173	0.173	0.984**				
	P	0.721**	0.762**	0.609**	0.712**	0.828**	0.069	-0.156	0.156	0.849**				
TSS (°Brix)	G	-0.115	-0.142	-0.240	-0.080	-0.303	-0.711**	0.173	-0.173	-0.448**	-0.336**			
	P	-0.112	-0.143	-0.224	-0.082	-0.296	-0.387**	0.161	-0.161	-0.430**	-0.256			
Ascorbic acid content (mg/100 g)	G	-0.110	-0.114	-0.342**	-0.073	-0.162	0.255	0.275	-0.275	-0.131	-0.171	0.016		
	P	-0.107	-0.100	-0.314	-0.073	-0.152	0.142	0.257	-0.257	-0.160	-0.145	0.015		
Chlorophyll content (mg/g)	G	0.519**	0.527**	0.464**	0.559**	0.507**	0.091	0.179	-0.179	0.356**	0.433**	-0.166	-0.010	
	P	0.496**	0.500**	0.450**	0.531**	0.479**	0.017	0.158	-0.158	0.329**	0.357**	-0.151	-0.004	
Yield/plant (g)	G	0.912**	0.937**	0.593**	0.903**	0.966**	0.199	-0.111	0.111	0.955**	0.955**	-0.238	-0.114	0.428**
	P	0.894**	0.910**	0.572**	0.883**	0.936**	0.132	-0.114	0.114	0.897**	0.839**	-0.231	-0.103	0.398**

** Significant at $p \leq 0.05$.

Table 4. Estimates of genotypic (G) and phenotypic (P) correlation coefficients for different pair of traits in coriander under hydroponic system

Traits	No. of leaves per plant	No. of branches per plant	Petiole length (cm)	Leaf area (cm ²)	Root length (cm)	Plant spread (cm ²)	Days to market-able harvest	Dry matter (%)	Moisture (%)	Plant height (cm)	No. of cuttings	TSS (° Brix)	Ascorbic acid content (mg/100 g)	Chloro-phyll content (mg/g)
No. of branches per plant	G 0.991**	P 0.979**												
Petiole length (cm)	G 0.842**	0.841**												
	P 0.802**	0.818**												
Leaf area (cm ²)	G 0.927**	0.930**	0.940**											
	P 0.904**	0.918**	0.921**											
Root length (cm)	G 0.916**	0.910**	0.902**	0.986**										
	P 0.830**	0.824**	0.822**	0.900**										
Plant spread (cm ²)	G 0.900**	0.899**	0.918**	0.982**	0.986**									
	P 0.868**	0.884**	0.891**	0.960**	0.886**									
Days to marketable harvest	G 0.387**	0.390**	0.124	0.238	0.259	0.287								
	P 0.280	0.300	0.081	0.168	0.132	0.235								
Dry matter (%)	G -0.128	-0.074	-0.269	-0.147	-0.099	-0.140	0.082							
	P -0.121	-0.072	-0.266	-0.147	-0.093	-0.134	0.063							
Moisture (%)	G 0.128	0.074	0.269	0.147	0.099	0.140	-0.082	-1.000**						
	P 0.121	0.072	0.266	0.147	0.093	0.134	-0.063	-1.000**						
Plant height (cm)	G 0.814**	0.862**	0.753**	0.913**	0.902**	0.905**	0.285	-0.000	0.000					
	P 0.725**	0.783**	0.666**	0.814**	0.689**	0.810**	0.277	-0.001	0.001					
No. of cuttings	G 0.899**	0.943**	0.810**	0.912**	0.893**	0.904**	0.386**	-0.117	0.117	0.933**				
	P 0.838**	0.885**	0.751**	0.865**	0.714**	0.828**	0.275	-0.112	0.112	0.831**				
TSS (°Brix)	G 0.173	0.137	-0.039	-0.029	0.030	-0.120	-0.180	0.246	-0.246	-0.214	-0.103			
	P 0.169	0.134	-0.031	-0.028	0.029	-0.117	-0.132	0.237	-0.237	-0.180	-0.077			
Ascorbic acid content (mg/100 g)	G -0.608**	-0.619**	-0.706**	-0.703**	-0.754**	-0.720**	0.097	0.184	-0.184	-0.703**	-0.627**	0.006		
	P -0.561**	-0.567**	-0.613**	-0.619**	-0.636**	-0.640**	0.020	0.163	-0.163	-0.578**	-0.536**	0.002		
Chlorophyll content (mg/g)	G 0.592**	0.584**	0.543**	0.648**	0.706**	0.738**	0.270	0.199	-0.199	0.573**	0.596**	-0.099	-0.350**	
	P 0.542**	0.548**	0.508**	0.628**	0.610**	0.680**	0.163	0.181	-0.181	0.446**	0.549**	-0.102	-0.277	
Yield/plant (g)	G 0.886**	0.905**	0.792**	0.930**	0.921**	0.943**	0.374**	-0.105	0.105	0.971**	0.949**	-0.197	-0.707**	0.679**
	P 0.856**	0.884**	0.761**	0.903**	0.828**	0.915**	0.246	-0.100	0.100	0.846**	0.873**	-0.189	-0.614**	0.643**

** Significant at $p \leq 0.05$.

acid content were negatively correlated at the genotypic level. These observations are consistent with earlier findings in coriander (*C. sativum*). Previous works reported strong positive correlations of leaf yield per plot with plant weight, number of leaves per plant, plant height and number of primary and secondary branches, emphasising the contribution of vegetative growth traits to yield improvement (23). The positive associations between plant weight, number of shoots and leaf weight, with particularly strong relationships between leaf weight and stem biomass (15). Similarly, the increased leaf area and branching resulted in higher leaf yield across varieties (24). The traits associated with enhanced leaf growth rates and photosynthetic efficiency were positively linked to yield performance (25), while another result confirmed that plant height, leaf number and branching intensity are reliable selection indices for improving leaf yield in coriander (26).

Path analysis

Path coefficient analysis conducted at both phenotypic and genotypic levels for the geponic system is summarised in Table 5, illustrating the magnitude of direct and indirect contributions of various attributes to yield per plant. At the phenotypic level, plant spread emerged as the most influential trait with the strongest positive direct contribution to yield, followed sequentially by plant height, number of leaves per plant, number of cuttings, leaf area, total soluble solids, days to marketable harvest, ascorbic acid content and number of branches per plant. In contrast, root length exerted the largest negative direct effect on yield, followed by moisture content, dry matter accumulation, chlorophyll content and petiole length. At the genotypic level, the number of leaves per plant showed the highest positive direct contribution to yield per plant, followed by plant spread, ascorbic acid content, number of branches per plant, root length and chlorophyll content. Conversely, the strongest negative direct influence on yield was observed for total soluble solids, followed by dry matter content, days to marketable harvest, moisture content, number of cuttings, plant height, leaf area and petiole length. With respect to indirect effects in the geponic system, phenotypic analysis revealed that number of branches per plant, followed by number of leaves, leaf area, plant height, root length and number of cuttings, contributed the greatest positive indirect effects on yield through plant spread. At the genotypic level, petiole length contributed the highest indirect effect on yield via number of leaves per plant, followed by number of branches per plant, number of cuttings, root length, leaf area, chlorophyll content, plant height and plant spread. The residual effects were low, with values of 0.1303 at the genotypic level and 0.0597 at the phenotypic level, indicating that the selected traits adequately explained variation in yield. Path coefficient analysis for the hydroponic system is presented in Table 6. At the phenotypic level, number of branches per plant exhibited the maximum positive direct effect on yield per plant, followed by plant spread, moisture content, dry matter, leaf area, number of cuttings, root length, chlorophyll content and plant height. In contrast, petiole length recorded the strongest negative direct effect, followed by total soluble solids, ascorbic acid content, days to marketable harvest and number of leaves per plant. At the genotypic level, dry matter content exerted the most pronounced positive direct effect on yield, followed by moisture content, number of leaves per plant, leaf area, root length, chlorophyll content, number of cuttings and number of branches per plant. The largest negative direct effects were

observed for total soluble solids, followed by plant spread, petiole length, plant height and days to marketable harvest. Regarding indirect contributions under hydroponic conditions, phenotypic analysis showed that number of leaves per plant had the strongest positive indirect influence on yield through number of branches per plant, followed by leaf area, plant spread, number of cuttings and root length. At the genotypic level, total soluble solids, chlorophyll content and ascorbic acid content exhibited the highest positive indirect effects on yield through dry matter accumulation. Residual effects were minimal, with values of 0.0068 and 0.0624 at genotypic and phenotypic levels respectively, indicating a strong explanatory power of the model. Overall, the results demonstrate that yield is largely governed by a few key traits that exert strong direct effects, while other characters contribute indirectly through their associations with these major components. Traits influencing leaf biomass and shoot development play a central role in determining yield performance. Consequently, these characters should receive priority in selection strategies aimed at improving yield and associated traits. Path coefficient analysis thus serves as a robust analytical tool for dissecting complex trait relationships in coriander (*C. sativum*), enabling breeders to distinguish between traits with true causal effects and those with secondary influences. Supporting this interpretation, early results reported that plant height and number of branches had major direct effects on leaf yield in coriander, while leaf area influenced yield indirectly through its interaction with these traits (27). Similarly, the trait number of branches per plant was the most decisive direct contributor to leaf yield, whereas plant height and leaf size primarily affected yield through their impact on branching patterns (28). These findings collectively underscore the importance of prioritising traits with strong direct effects in coriander breeding programs.

Conclusion

The existence of substantial genetic variability among the evaluated coriander genotypes provides a strong foundation for targeted improvement under protected cultivation. Traits such as number of leaves per plant, number of branches per plant, leaf area and plant spread exhibited high variability along with high heritability and genetic advance, indicating that these characters can be reliably improved through direct phenotypic selection. For plant breeders, this suggests that simple selection strategies focusing on these traits can lead to rapid genetic gains, particularly for yield improvement in controlled environments. The predominance of additive gene action further implies that early-generation selection would be effective, reducing time and resource requirements in breeding programs. From a grower's perspective, the strong positive association of yield per plant with morphological and physiological traits such as plant spread, number of cuttings, chlorophyll content and leaf area highlights practical indicators for identifying high-performing genotypes. Selection of varieties expressing vigorous vegetative growth and higher chlorophyll content can enhance productivity, especially in protected structures and hydroponic systems where uniform growth and repeated harvests are crucial. Path coefficient analysis confirmed that several of these traits directly influence yield, reinforcing their value as reliable selection criteria. Given that earlier research has focused on open-field cultivation, the

Table 5. Estimates of direct and indirect effects of different traits on yield per plant at genotypic (G) and phenotypic (P) levels in coriander under geponic system

Traits		No. of leaves per plant	No. of branches per plant	Petiole length (cm)	Leaf area (cm ²)	Root length (cm)	Plant spread (cm ²)	Days to marketable harvest	Dry matter (%)	Moisture (%)	Plant height (cm)	No. of cuttings	TSS (° Brix)	Ascorbic acid content (mg/100 g)	Chlorophyll content (mg/ g)	r
No. of leaves per plant	G	0.979	0.687	-0.066	-0.888	0.520	0.778	-0.259	0.270	-0.256	-0.178	-0.739	0.095	-0.083	0.052	0.912**
	P	0.284	0.004	-0.012	0.112	-0.190	0.358	0.004	0.009	-0.013	0.292	0.098	-0.012	-0.001	-0.039	0.894**
No. of branches per plant	G	0.966	0.693	-0.066	-0.821	0.527	0.835	-0.254	0.279	-0.264	-0.246	-0.794	0.118	-0.087	0.051	0.937**
	P	0.279	0.003	-0.012	0.111	-0.191	0.366	0.004	0.009	-0.013	0.306	0.104	-0.017	-0.001	-0.038	0.910**
Petiole length (cm)	G	0.974	0.773	-0.099	-0.405	0.420	0.465	-0.107	0.449	-0.372	-0.859	-0.633	0.210	-0.270	0.046	0.593**
	P	0.187	0.002	-0.019	0.075	-0.150	0.264	0.001	0.048	-0.066	0.210	0.083	-0.024	-0.004	-0.035	0.572**
Leaf area (cm ²)	G	0.844	0.654	-0.067	-0.444	0.213	0.666	-0.183	0.427	-0.404	-0.141	-0.729	0.067	-0.055	0.055	0.903**
	P	0.280	0.003	-0.012	0.114	-0.187	0.358	0.004	0.014	-0.019	0.284	0.095	-0.009	-0.001	-0.041	0.883**
Root length (cm)	G	0.852	0.448	-0.073	-0.227	0.564	0.405	-0.173	0.607	-0.575	-0.137	-0.789	0.044	-0.140	0.039	0.845**
	P	0.252	0.002	-0.013	0.099	-0.215	0.325	0.003	0.020	-0.027	0.278	0.101	-0.005	-0.002	-0.026	0.792**
Plant spread (cm ²)	G	0.675	0.573	-0.068	-0.326	0.490	0.898	-0.296	0.741	-0.702	-0.346	-0.852	0.252	-0.123	0.050	0.966**
	P	0.259	0.003	-0.013	0.104	-0.177	0.392	0.005	0.024	-0.033	0.330	0.112	-0.031	-0.002	-0.037	0.936**
Days to marketable harvest	G	0.323	0.141	-0.008	-0.148	0.077	0.304	-0.664	-0.589	0.463	-0.355	-0.137	0.590	0.193	0.009	0.199
	P	0.033	0.000	0.000	0.012	-0.021	0.057	0.035	-0.009	0.012	0.043	0.009	-0.040	0.002	-0.001	0.132
Dry matter (%)	G	-0.400	-0.165	0.039	0.916	-0.094	-0.600	-0.167	-0.702	0.506	0.318	0.156	-0.144	0.208	0.018	-0.111
	P	-0.021	0.000	0.007	-0.013	0.034	-0.076	0.003	-0.126	0.172	-0.080	-0.021	0.017	0.003	-0.012	-0.114
Moisture (%)	G	0.400	0.165	-0.039	-0.916	0.092	0.600	0.167	0.702	-0.506	-0.318	-0.156	0.146	-0.208	-0.018	0.111
	P	0.021	0.000	-0.007	0.013	-0.034	0.076	-0.003	0.126	-0.172	0.080	0.021	-0.017	-0.003	0.012	0.114
Plant height (cm)	G	0.748	0.684	-0.058	-0.247	0.342	0.783	-0.309	0.812	-0.769	-0.451	-0.888	0.372	-0.099	0.035	0.955**
	P	0.219	0.002	-0.010	0.085	-0.158	0.342	0.004	0.027	-0.036	0.379	0.115	-0.045	-0.002	-0.025	0.897**
No. of cuttings	G	0.888	0.529	-0.069	-0.421	0.393	0.532	-0.192	0.637	-0.605	-0.428	-0.502	0.280	-0.130	0.043	0.955**
	P	0.205	0.002	-0.011	0.081	-0.159	0.325	0.002	0.020	-0.027	0.321	0.136	-0.027	-0.002	-0.028	0.839**
TSS (°Brix)	G	-0.628	-0.312	0.024	0.636	-0.030	-0.910	0.898	-0.641	0.607	0.650	0.303	-0.831	0.012	-0.016	-0.238
	P	-0.032	0.000	0.004	-0.009	0.010	-0.116	-0.014	-0.020	0.028	-0.163	-0.035	0.104	0.000	0.012	-0.231
Ascorbic acid content (mg/100 g)	G	-0.601	-0.250	0.034	0.580	-0.204	-0.486	-0.322	-0.916	0.962	0.190	0.155	-0.014	0.758	-0.001	-0.114
	P	-0.030	0.000	0.006	-0.008	0.038	-0.060	0.005	-0.032	0.044	-0.061	-0.020	0.002	0.013	0.000	-0.103
Chlorophyll content (mg/g)	G	0.844	0.156	-0.046	-0.439	0.221	0.521	-0.115	-0.662	0.627	-0.516	-0.391	0.138	-0.008	0.098	0.428**
	P	0.141	0.001	-0.008	0.060	-0.072	0.188	0.001	-0.020	0.027	0.125	0.049	-0.016	0.000	-0.078	0.398**

** Significant at $p \leq 0.05$; residual effect=0.1303 (G) & 0.0597 (P).

Table 6. Estimates of direct and indirect effects of different traits on yield per plant at genotypic (G) and phenotypic (P) levels in coriander under hydroponic system

Traits		No. of leaves per plant	No. of branches per plant	Petiole length (cm)	Leaf area (cm ²)	Root length (cm)	Plant spread (cm ²)	Days to marketable harvest	Dry matter (%)	Moisture (%)	Plant height (cm)	No. of cuttings	TSS (° Brix)	Ascorbic acid content (mg/100 g)	Chlorophyll content (mg/g)	r
No. of leaves per plant	G	0.758	0.094	-0.263	0.634	0.200	-0.814	-0.022	-0.494	0.489	-0.095	0.206	-0.105	0.144	0.155	0.886**
	P	-0.055	0.540	-0.297	0.163	0.079	0.266	-0.020	-0.028	0.031	0.049	0.082	-0.034	0.041	0.038	0.856**
No. of branches per plant	G	0.751	0.095	-0.263	0.636	0.193	-0.813	-0.022	-0.285	0.282	-0.101	0.216	-0.083	0.146	0.153	0.905**
	P	-0.053	0.552	-0.303	0.166	0.079	0.271	-0.021	-0.017	0.019	0.053	0.087	-0.027	0.041	0.038	0.884**
Petiole length (cm)	G	0.638	0.079	-0.313	0.643	0.181	-0.850	-0.007	-0.038	0.029	-0.088	0.185	0.024	0.167	0.142	0.792**
	P	-0.044	0.451	-0.371	0.166	0.078	0.273	-0.006	-0.061	0.068	0.045	0.074	0.008	0.045	0.035	0.761**
Leaf area (cm ²)	G	0.703	0.088	-0.294	0.684	0.292	-0.980	-0.013	-0.565	0.560	-0.107	0.209	0.018	0.166	0.170	0.930**
	P	-0.049	0.507	-0.341	0.181	0.086	0.294	-0.012	-0.034	0.038	0.055	0.085	0.004	0.045	0.044	0.903**
Root length (cm)	G	0.694	0.086	-0.282	0.675	0.310	-0.987	-0.015	-0.383	0.379	-0.106	0.204	-0.018	0.178	0.185	0.921**
	P	-0.045	0.455	-0.305	0.163	0.095	0.272	-0.009	-0.021	0.024	0.046	0.070	-0.006	0.046	0.042	0.828**
Plant spread (cm ²)	G	0.682	0.085	-0.787	0.672	0.291	-0.516	-0.016	-0.538	0.533	-0.106	0.207	0.073	0.170	0.194	0.943**
	P	-0.047	0.488	-0.331	0.173	0.084	0.307	-0.016	-0.031	0.034	0.054	0.081	0.024	0.047	0.047	0.915**
Days to marketable harvest	G	0.293	0.037	-0.039	0.163	0.340	-0.578	-0.056	0.316	-0.313	-0.033	0.088	0.109	-0.023	0.071	0.374**
	P	-0.015	0.165	-0.030	0.030	0.013	0.072	-0.070	0.015	-0.016	0.019	0.027	0.027	-0.001	0.011	0.246
Dry matter (%)	G	-0.097	-0.007	0.084	-0.100	-0.130	0.282	-0.005	0.854	-0.818	0.000	-0.027	-0.150	-0.044	0.052	-0.105
	P	0.007	-0.040	0.099	-0.026	-0.009	-0.041	-0.004	0.230	-0.257	0.000	-0.011	-0.048	-0.012	0.013	-0.100
Moisture (%)	G	0.097	0.007	-0.084	0.100	0.130	-0.282	0.005	-0.854	0.818	0.000	0.027	0.150	0.044	-0.052	0.105
	P	-0.007	0.040	-0.099	0.026	0.009	0.041	0.004	-0.230	0.257	0.000	0.011	0.048	0.012	-0.013	0.100
Plant height (cm)	G	0.617	0.081	-0.235	0.625	0.181	-0.824	-0.016	-0.002	0.002	-0.117	0.214	0.130	0.166	0.150	0.971**
	P	-0.040	0.432	-0.247	0.147	0.066	0.248	-0.019	0.000	0.000	0.067	0.082	0.037	0.042	0.031	0.846**
No. of cuttings	G	0.681	0.089	-0.253	0.624	0.170	-0.822	-0.022	-0.452	0.448	-0.109	0.229	0.062	0.148	0.156	0.949**
	P	-0.046	0.488	-0.278	0.156	0.068	0.254	-0.019	-0.026	0.029	0.056	0.098	0.016	0.039	0.038	0.873**
TSS (°Brix)	G	0.131	0.013	0.012	-0.020	0.039	0.242	0.010	0.949	-0.940	0.025	-0.023	-0.608	-0.001	-0.026	-0.197
	P	-0.009	0.074	0.012	-0.005	0.003	-0.036	0.009	0.055	-0.061	-0.012	-0.008	-0.203	0.000	-0.007	-0.189
Ascorbic acid content (mg/100 g)	G	-0.461	-0.058	0.221	-0.481	-0.087	0.452	-0.005	0.711	-0.604	0.080	-0.143	-0.004	-0.236	-0.092	-0.707**
	P	0.031	-0.313	0.227	-0.112	-0.061	-0.196	-0.001	0.038	-0.042	-0.039	-0.053	0.000	-0.073	-0.019	-0.614**
Chlorophyll content (mg/g)	G	0.348	0.055	-0.670	0.043	0.924	-0.489	-0.015	0.767	-0.760	-0.067	0.136	0.060	0.085	0.262	0.679**
	P	-0.030	0.303	-0.188	0.114	0.058	0.208	-0.011	0.042	-0.046	0.030	0.054	0.021	0.020	0.069	0.643**

** Significant at $p \leq 0.05$; residual effect=0.0068 (G) & 0.0624 (P).

present study fills an important gap by identifying yield-determining traits specifically suited to protected agriculture. The results provide actionable guidelines for breeders in developing environment-specific coriander varieties and for growers in choosing suitable genotypes and management practices to maximise yield and resource-use efficiency under controlled growing conditions.

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Authors' contributions

V and PS¹ performed the experiment. SK, PS² designed the research. PS¹ wrote the manuscript. PS², AK, AP and HT revised and corrected the manuscript. All authors have contributed for different sections of writing, reviewing, correction and statistical analysis. All authors read and approved the final manuscript [PS¹-Parveen Sharma; PS²-Payal Sharma¹].

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

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