CORRELATION AND PATH ANALYSIS OF DRY WEIGHT IN SUMMER SAVORY (*Satureja hortensis* L.) BASED ON MORPHOLOGICAL CHARACTERISTICS

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Abstract. The development of new summer savory (*Satureja hortensis* L.) varieties in genetic improvement programs requires well-structured methods for managing trait interrelationships. This study employs correlation coefficients and path analysis to identify the relationships between plant dry weight performance in summer savory and various morphological traits. Twenty-nine genotypes were cultivated to determine the key components influencing yield performance. The correlation analysis revealed positive and significant associations between plant dry weight and root. Essential oil content demonstrated no significant positive or negative association with other measured traits, except for a connection with leaflets per main stem. Plant height and stem length exhibited positive, significant associations with internode distance, leaf area in the leaves located in the main and lateral branches, and leaf area of lateral branch leaves. Conversely, these traits were negatively associated with root length, leaflets per main stem, and root dry weight. Path analysis identified stem length and root dry weight as primary traits with direct positive impacts on plant dry weight performance. These findings were validated using the bootstrapping method, which confirmed the significant association between plant dry weight and other morphological characteristics. Additionally, certain traits such as plant height, root length, internode distance, and leaflets per main stem were classified as secondary, tertiary, and quaternary order variables, underscoring their notable influence on yield performance. Thus, the traits most strongly related to yield performance include root characteristics, plant height, and leaflets. These findings can inform the genetic improvement processes aimed at enhancing yield performance.

Key words: collinearity; direct effects; indirect effects; multiple regression; yield perforamnce.

INTRODUCTION

Many species of *Satureja* are rich in carvacrol and are used in various regions as both vegetables and medicinal plants. *S. hortensis*, an annual, vegetable crop routinely cultivated, is used fresh as a vegetable or dried as leaves in folk medicine to treat certain stomach ailments [11, 14]. Additionally, it possesses antioxidative and antimicrobial properties due to components like carvacrol, thymol, γ-terpinene and p-cymene [16, 24]. *S. hortensis* is native to southern Europe and southwest Asia [18, 23], and it is widely cultivated in Iran, particularly in the western and northwestern regions. The yield performance of plants depends on genetic variation as well as environmental factors, farming practices and environmental stresses [1]. Evaluating different genotypes under consistent environmental conditions reveals genetic diversity, while studies on the same cultivars in varying environments help identify non-genetic variability [2, 10]. In medicinal plant breeding, limited genetic diversity can restrict progress toward optimal performance, making the evaluation of genetic variation crucial for designing effective genetic improvement programs. Morphological traits offer practical, cost-effective approaches for assessing genetic variation in plants, despite some inherent limitations.

Factors such as natural selection, mutagen exposure, and genetic drift contribute to genetic variation, the evaluation of which supports conservation planning and breeding strategies [6, 22]. The floras of taxonomists provide a baseline for genetic conservation programs, aiding in genetic improvement projects. In these efforts, morphological and agronomic diversity within and between accessions are typically assessed in subsequent stages. For example, Bezic *et al.* [4] reported significant differences in essential oil percentages between populations of *S. montana* and *S. cuneifolia*, despite their similar essential oil compositions. In a study by Hadian *et al.* [9], 69 samples from eight populations of *S. khuzistanica* Jamzad revealed that morphological diversity was most pronounced in flower length and leaf area, with individual groupings unrelated to geographic distribution. Further research on *Satureja bachtiarica* by Khadivi-Khub *et al.* [13], found that leaf properties were related to flower and inflorescence properties positively, and plant height showed a positive association with inflorescence traits. Karimi *et al.* [11] examined 60 accessions from seven *Satureja* populations in northern and northeastern areas of Iran, grouping them into three distinct clusters based on morphological traits, with essential oil content varying from 0.2% to 5%.

In a study on genetic diversity in *S. hortensis* genotypes collected from various regions in Iran, significant variation was observed in traits such as leaf number, hundred-seed weight, and seed count per plant. The highest correlations were found between leaf number and leaf yield, hundred-seed weight, and seed count [8]. Collecting accessions and conducting initial characterizations are essential for the conservation of plant materials and for genetic improvement projects aimed at developing high-performing cultivars. Additional research is necessary to identify optimal production management practices and key traits that significantly impact yield performance [27]. Identifying these traits will enhance the potential for achieving genetic improvement goals. Multivariate

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statistical methods, such as association coefficients, multiple regression models, hierarchical clustering, principal component analysis, factor analysis, and path coefficient analysis, are useful for identifying key traits that influence yield performance and for establishing selection indices in genetic improvement projects. While some of these methods do not account for causal relationships, path coefficient analysis specifically addresses causal associations among measured traits, based on either theoretical or empirical evidence. Path analysis can clarify the significance of each trait; however, strong associations among traits can introduce collinearity, complicating the interpretation of the true effect in each trait. Mehravi *et al.* [17], in anise (*Pimpinella anisum* L.) and Zavoshti *et al.* [28], common sainfoin (*Onobrychis viciifolia* Scop.), used path analysis by organizing predictors into primary-, secondary-, tertiary-, and quaternary-order traits to explore relationships between target traits and their components. This approach has advantages for understanding predictor value and improving model fit. The target of the current study is to find the role of various traits on yield performance and to guide plant breeders in identifying traits that can be utilized in genetic improvement programs for summer savory. It is hypothesized that variation in morphological and agronomic traits among *Satureja hortensis* genotypes significantly influences yield performance, and that specific key traits can be identified as reliable predictors for selection in genetic improvement programs.

MATERIALS AND METHODS

Experimental design

In this research, seeds from 29 distinct accessions of Iranian summer savory were carefully gathered from different regions across Iran, each presenting unique geographical and environmental characteristics (Table 1). The experiment was conducted at the research farm of University of Mohaghegh Ardabili, Ardabil (38°15′N, 48°17′E), situated in Iran, during the spring growing season. Seeds were sown on May, and the plants were grown for about three monsths until flowering. The goal was to capture a broad spectrum of genetic variation within the species. The study followed a randomized block design, a well-established approach that minimizes experimental variability by randomly assigning treatments within blocks (Fig. 1). Each block included three replications to ensure statistical accuracy. The sowing of seeds was done in four rows, with 20 cm spacing between rows and between individual plants within the rows. This arrangement was intended to promote optimal air circulation and light penetration, both essential for healthy plant growth. During the flowering phase, five plants from the central row of each plot were individually harvested to ensure consistent environmental exposure and minimize edge effects, which can introduce variability into the results.

Measured traits

The morphological assessment focused on fourteen specific traits, representing various aspects of plant

Table 1. Name and collection site of 29 summer savory genotypes

Code	Name	Site	Code	Site	Provence
G1	Shush	Khuzestan	G16	Tabriz-B	East-Azarbaijan
G2	Tabriz-I	East-Azarbaijan	G17	Isfahan	Isfahan
G3	Ardabil	Ardabil	G18	Qazvin	Qazvin
G4	Razan-I	Isfahan	G19	Tuserkan-I	Hamadan
G5	Mashhad	Razavi Khorasan	G20	Ilam	Ilam
G6	Sistan	Sistan and Baluchistan	G21	Borujerd	Lorestan
G7	Tonkabon-II	Mazandaran	G22	Kelachay	Gilan
G8	Shiraz	Fars	G23	Arak	Markazi
G9	Qom	Qom	G24	Dezful	Khuzestan
G10	Kermanshah	Kermanshah	G25	Razan-B	Isfahan
G11	Sanandaj	Kurdistan	G26	Tehran	Tehran
G12	Parsabad	Ardabil	G27	Tonkabon-I	Mazandaran
G13	Sardasht	West-Azarbaijan	G28	Sarab	East-Azarbaijan
G14	Tuserkan-II	Hamadan	G29	Qeshm	Hormozgan
G15	Hamedan	Hamadan			

Figure 1. The cultivated genotypes of summer savory in the field

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growth and structure. This evaluation was conducted systematically, focusing on key characteristics from ten randomly selected samples. These traits included: plant height (PH), stem length (SL), root length (RL), internode distance (DI), number of leaflets per main stem (LMS), plant dry weight (PDW), root dry weight (RDW), essential oil content (EO), leaf area of main stem leaves (LAMS), and leaf area of lateral branch leaves (LALB). Weight-related traits were recorded using an electronic balance with a precision of 0.1 g, ensuring accurate biomass measurements. The total plant height was measured from the base to the apex with a ruler, offering insights into the growth potential of each genotype. Stem and root lengths, as well as internode distances, were measured with a ruler, and the number of leaflets on the main stem was counted. The leaf area for both main stem and lateral branch leaves was determined by sampling leaves from the first, middle, and terminal position.

Statistical analysis

The normality of the data for the measured traits was first evaluated using Minitab 17.0, through the Ryan-Joiner test, which examines the degree of alignment between the data and normal distribution scores. Next, the association coefficients between the traits were computed via IBM-SPSS 25.0. To gain deeper insights into the relationships between traits and identify those with the greatest influence on yield performance, path analysis was employed. A stepwise regression model was initially fitted, with dry leaf yield as the response attribute and the remaining characteristics as predictor attributes, enabling the identification of traits that most effectively explained variability in yield performance. Path coefficient analysis was then done to compute both the directly and indirectly influencing paths on leaf dry yield, with subsequent steps incorporating other dependent traits. To validate the results and assess their reliability, 1,000 resamples were bootstrapped, allowing for the calculation of average values, bias magnitude between these averages and the original path coefficients, and standard deviations. Differences between the bootstrapped results and the path coefficients were then evaluated. Additionally, to assess multicollinearity, tolerance and variance inflation factors were calculated using IBM-SPSS 25.0, and path diagrams were generated using AMOS 21.0 [26]. This comprehensive approach enabled a thorough examination of trait interrelationships and their impact on yield performance, ensuring the robustness and reliability of the findings of the current study.

RESULTS

According to the correlation coefficients among traits of summer savory (Table 2), plant height (PH) showed significant positive associations with stem length (SL), internode distance (DI), leaf area of main stem leaves (LAMS), and leaf area of lateral branch leaves (LALB). Conversely, PH had significant negative associations with root length (RL), leaflets per main stem (LMS), and root dry weight (RDW). Similarly, stem length (SL) was positively associated with DI, LAMS, and LALB, while negatively associated with RL, LMS, and RDW. Root length, in turn, was associated positively with LMS and RDW but associated negatively with DI (Table 2). Internode distance (DI) was associated positively with LAMS and LALB and associated negatively with LMS and RDW. Additionally, LMS had negative associations with RDW, LAMS, and LALB, while showing a positive association with EO content (Table 2). To uncover the most reliable patterns in these associations and explore the direct as well as indirect effects of traits on plant dry weight (PDW), path analysis is essential. This approach provides deeper insights into the complex relationships among traits and their collective impact on performance, supporting informed decisions in summer savory breeding efforts. To evaluate the significance of traits in relation to PDW, a multiple regression model was fitted, and collinearity indices were calculated (Table 3). Initially, all traits were considered as primary-order with respect to PDW, and the path coefficients (or direct effects) were extracted. The collinearity indices provided insights into trait interrelationships and their influence on PDW. Although the collinearity indices were generally not high, plant height (PH) and stem length (SL) exhibited elevated collinearity values (Table 3). However, when traits were organized into primary-, secondary-, tertiary-, and quaternary-order categories with PDW as the target trait, the high variance inflation factors (VIF) for PH and SL dropped significantly, from 37.61 to 1.16 for PH and from 57.67 to 1.30 for SL (Table 4).

Table 2. Magnitudes of correlations for traits of 29 summer savory genotypes

	PH	SL	RL	DI	LMS	PDW	RDW	EO	LAMS
SL	0.95								
RL	-0.37	-0.60							
DI	0.82	0.90	-0.62						
LMS	-0.61	-0.71	0.45	-0.81					
PDW	0.05	-0.02	0.32	-0.08	0.12				
RDW	-0.39	-0.48	0.49	-0.44	0.46	0.78			
EO	-0.10	-0.20	0.25	-0.30	0.51	-0.07	0.02		
LAMS	0.40	0.48	-0.23	0.57	-0.69	0.18	-0.07	-0.32	
LALB	0.39	0.50	-0.36	0.53	-0.60	0.24	-0.02	-0.37	0.70

Critical values of significant correlations are 0.37 and 0.47 at 0.05 and 0.01 probability level. Abbreviations: plant height (PH), stem length (SL), root length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), root dry weight (RDW), essential oil (EO), leaf area of main stem's leaves (LAMS), and leaf area of lateral branches' leaves (LALB).

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Table 3. Standardized and unstandardized coefficients of first-order traits on the plant dry weight of 29 summer savory genotypes and collinearity indices

	b†	t‡	Sig.	SE§	Beta¶	Tolerance	VIF©
PH	-0.36	-1.28	0.22	0.284	-0.78	0.03	37.61
SL	0.65	2.19	0.04	0.297	1.65	0.02	57.67
RL	0.51	1.57	0.13	0.327	0.39	0.16	6.18
DI	-1.26	-1.02	0.32	1.232	-0.32	0.10	9.88
LMS	-0.02	-0.29	0.78	0.068	-0.07	0.15	6.89
RDW	18.56	6.50	0.00	2.857	0.97	0.44	2.25
EO	-0.03	-0.03	0.98	1.065	0.00	0.57	1.74
LAMS	-0.61	-0.33	0.74	1.848	-0.06	0.33	3.04
LALB	0.61	0.28	0.78	2.200	0.04	0.40	2.53

† b, regression coefficient; ‡t, t-test statistics; §SE, standard error; ¶ Beta, standardized regression coefficient or path coefficient; ©VIF, variance inflation factor. Abbreviations: plant height (PH), stem length (SL), root length (RL), distance of internodes (DI), leaflets per main stem (LMS), root dry weight (RDW), essential oil (EO), leaf area of main stem's leaves (LAMS), and leaf area of lateral branches' leaves (LALB).

Table 4. Standardized beta (path coefficients) and collinearity indices for predictor traits in stepwise regression analysis, predictors arranged into primary-, secondary-, tertiary-, and quaternary-order traits

Variables		Unstandardized coefficients				Collinearity		Path's	R^2
Y†	X‡	Slope	SE§	t¶	Sig.	Tolerance	VIF©	Beta	
PDW	RDW	19.07	2.105	9.06	0.000	0.77	1.30	0.99	0.74
	SL	0.18	0.043	4.13	0.000	0.77	1.30	0.45	
SL	PH	1.00	0.041	24.31	0.000	0.86	1.16	0.84	0.21
	RL	-0.98	0.117	-8.41	0.000	0.86	1.16	-0.29	
RDW	RL	0.03	0.012	2.93	0.007	1.00	1.00	0.49	0.97
RL	DI	-1.85	0.449	-4.12	0.000	1.00	1.00	-0.62	0.36
PH	DI	6.97	0.927	7.52	0.000	1.00	1.00	0.82	0.67
DI	LMS	-0.05	0.007	-7.26	0.000	1.00	1.00	-0.81	0.65

† Response variable, ‡ Predictor variable, § Standard error, ¶ t statistic, © VIF, Variance inflation factor. Abbreviations: plant height (PH), stem length (SL), root length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), and root dry weight (RDW).

This path analysis approach, which incorporates collinearity indices and clarifies the contribution each trait in various path elements, is comparable to similar findings in vegetable and field crops such as *Triticum aestivum* [3], *Coriandrum sativum* [15], *Brassica juncea* [19], *Gossypium hirsutum* [21], and *Onobrychis viciifolia* [28]. These results suggest that the current method should be effective for extracting valuable insights in summer savory breeding.

The corrected coefficient of determination (R^2) for the fitted stepwise regression model (74%) highlighted the significant roles of root dry weight (RDW) and stem length (SL) as primary-order traits in explaining the variation in plant dry weight (PDW) (Table 4). Notably, RDW showed a larger direct effect (0.99) compared to SL (0.45). To obtain reliable estimates for direct effects with appropriate standard error values and minimal bias, resampling via bootstrapping was conducted (Table 5). Using one thousand resamples, small standard errors and minimal bias values were observed for all direct effects, confirming the statistical robustness and reliability of the path analysis results. Collinearity among traits did not affect the results, as the stepwise regression model and the classification of traits into primary-, secondary-, tertiary-, and quaternary-order traits helped mitigate this issue. In multiple regression models, predictor traits ideally should not be interdependent at each step; however, intricate correlations among traits can lead to collinearity issues. Grouping traits into various orders alleviates this problem, as demonstrated in other vegetable crops like *Coriandrum sativum* [15]. This approach, supported by resampling via bootstrapping, provides a more nuanced understanding of trait interrelationships and enhances the reliability of path analysis findings.

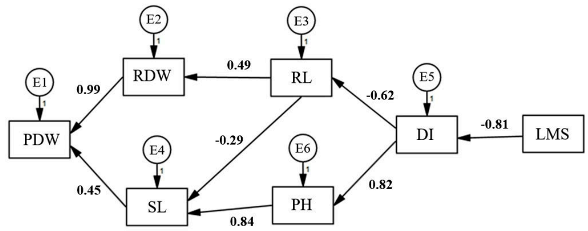

Figure 2. Path diagram of the associations among measured traits influencing to dry yield. Abbreviations: plant height (PH), stem length (SL), root length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), and root dry weight (RDW).

Plant height had a positive direct effect on plant dry weight as a secondary-order trait, contributing to the variation in plant dry weight, while stem length showed a negative direct effect on this trait (Table 4). Root length, as a secondary-order trait, also demonstrated a positive direct effect on root dry weight (0.49), explaining variation in root dry weight (Table 4). All of these direct effects were validated through bootstrapping with one thousand resamples, resulting in low bias (Table 5). Among tertiary-order traits, only internode distance (DI) was identified, exerting both a positive effect on plant height (0.82) and a negative

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Table 5. Bootstrapping of direct effects of primary-, secondary-, secondary-, tertiary-, and quaternary-order traits

Variables		Bootstrapping			95% CI¶	
Y†	X‡	Mean	Bias	SE§	Lower	Upper
PDW	RDW	0.99	0.007	0.082	0.839	1.163
	SL	0.45	0.019	0.102	0.299	0.710
SL	PH	0.84	0.011	0.058	0.792	1.018
	RL	-0.29	-0.005	0.033	-0.379	-0.245
RDW	RL	0.49	0.018	0.170	0.220	0.880
RL	DI	-0.62	-0.028	0.141	-1.068	-0.487
PH	DI	0.82	-0.053	0.172	0.304	0.978
DI	LMS	0.57	-0.005	0.176	0.166	0.907

† Response variable, ‡ Predictor variable, § Standard error, ¶ Confidence interval. Abbreviations: plant height (PH), stem length (SL), root length (RL), distance of internodes (DI), leaflets per main stem (LMS), plant dry weight (PDW), and root dry weight (RDW).

Table 6. Amounts of direct and indirect values for the predictor traits in path analysis across both trials (arranged into primary-order traits as well as secondary-order traits)

Response	Predictor			Response	Predictor		
		RDW	SL			PH	RL
PDW	RDW	0.993	-0.217	SL	PH	0.841	0.107
	SL	-0.477	0.453		RL	-0.310	-0.291

Abbreviations: plant height (PH), stem length (SL), root length (RL), plant dry weight (PDW), and root dry weight (RDW).

effect on root length (-0.62). Finally, leaflets per main stem, as a quaternary-order trait, had a negative direct effect (-0.81) on internode distance.

The indirectly affected path of root dry weight on plant dry weight through stem length was negative (-0.217), and similarly, the indirect effect of stem length on plant dry weight via root dry weight was also negative (-0.477) (Table 6). Conversely, the indirectly affected path of plant height on root length was positive (0.107), while the indirectly affected path of root length on plant height was negative (-0.310) (Table 6). These findings underscore the significance of root-related traits (length and weight), height-related traits (such as plant height, stem length, and internode length), and the number of leaflets per main stem in influencing plant dry weight in summer savory. These traits were classified into primary-, secondary-, tertiary-, and quaternary-order categories based on their roles. To enhance the presentation of the results, a path diagram was constructed (Fig. 2), which visually represents the statistical findings. This diagram was generated using AMOS software and validated through various fit indices (Table 7). Most of these indices were statistically significant, confirming the accuracy of the fiited model. In the present model, the CMIN/df value of 2.14 therefore indicates an acceptable model fit, whereas comparative fit index (CFI), the normed fit index and incremental fit index values were considered acceptable, confirming that the proposed model fits the data reasonably well. The non-centrality parameter (NCP) value, suggested low to moderate misspecification (Table 7), therfore considering the combination of fit indices, the proposed path model demonstrates acceptable to good fit. While many studies use point and interval estimation to achieve reliable results, bootstrapping as a resampling method ensures dependable statistical values, including standard errors and bias [2]. In this study, with one thousand resamples, bootstrapping yielded minimal standard errors and low bias for the direct effects. As a result, the robustness of the fitted path model was confirmed, providing trustworthy results and addressing any collinearity concerns. By grouping traits into primary-, secondary-, tertiary-, and quaternary-order categories, the collinearity issue was effectively resolved.

DISCUSSION

For breeding and selecting desirable individuals in summer savory, it is essential to assess the variability of traits within the current germplasm. By using path analysis to quantify both directly and indirectly affected paths of traits on yield performance, we gain a deeper understanding of how yield-related traits influence overall yield. The primary advantage of path analysis is its ability to identify the key factors that directly impact a target trait and reveal how other traits indirectly influence it through their interrelationships. Previous studies have shown that path analysis provides more insight into the relationships among yield components than simple correlation alone [27]. Additionally, path analysis helps determine if a compensation phenomenon is occurring, where different factors may counterbalance each other's effects on the target trait. Positive corrleations were found between plant dry weight and root dry weight, which is consistent with the findings of Nikrouz-Gharamaleki *et al.* [20], who reported similar correlations in summer savory, especially between whole plant dry weight and root dry weight. Furthermore, leaf area of lateral branch leaves exhibited a negative association with essential oil content, but a positive association with leaf area of main stem leaves. Fathi *et al.* [8] observed that the essential oil percentage of summer savory was

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positively correlated with the number of days to flowering and the number of leaves per plant. These identified associations provide insights into the interrelationships among measured traits, which can facilitate trait evaluation and allow for indirect trait measurement where direct measurement is challenging. When a trait is difficult to measure or requires expensive equipment, associated traits with significant correlations can be used as proxies for indirect measurement. This approach allows for efficient and cost-effective trait evaluation in breeding programs. This study demonstrates the advantages of using path analysis over traditional methods for detecting both direct and indirect influences of various traits. The correlation results and path analysis revealed relatively strong associations between plant dry weight and several key traits. The most influential traits related to yield performance were root characteristics, plant height, and leaflets per main stem. These traits can be leveraged in genetic improvement programs to enhance yield performance. Therefore, selecting individuals with high values for these traits is recommended, particularly for improving production and selection in summer savory. In other words, these traits are critical for the selection process in genetic improvement projects, aiming to enhance the performance of summer savory under field conditions.

The significant roles of leaf properties, such as plant height, stem length, root length, internode distance, leaflets per main stem, and root dry weight in influencing plant dry weight, are well-established in leafy vegetables like *Ocimum* basilicum [5], and *Lactuca sativa* [25]. However, there are few reports for summer savory, making this study the first to detail the actual role of these yield components in the leaf yield performance of summer savory. Katar *et al.* [12], reported that plant fresh weight and leaf fresh weight are the main traits influencing dry leaf weight in summer savory. However, these traits likely show high collinearity with target yield, suggesting that removing them from the analysis could help isolate the most influential traits on yield performance. Summer savory can be classified as both a vegetable crop and a medicinal plant, making it a valuable addition to human diets and an important contributor to food security [7]. The plant dry weight productivity of summer savory is influenced by various traits, with root characteristics, plant height, and leaflets being identified as the most significant. These traits should therefore be used to define selection indices in breeding programs. Additionally, root length, as a secondary-order trait, had both positive and negative direct effects on root dry weight and plant height, respectively, while distance of internodes, as a tertiary-order trait, had both positive and negative direct effects on plant height and root length. Finally, leaflets per main stem, as a quaternary-order trait, showed a negative direct effect on the distance of internodes. These findings suggest that these traits should be prioritized in subsequent breeding steps, with particular attention to root length, which requires more careful consideration. Breeding efforts focused on enhancing these key traits have the potential to significantly improve yield performance in a positive direction.

In addition to direct effects, the path analysis highlighted several important indirect relationships among morphological traits and their influence on plant dry weight, whereas root dry weight exhibited a negative indirect effect on PDW through stem length, suggesting that while RDW directly enhances PDW, increases in SL may partially offset the contribution of RDW. Similarly, the indirect effect of SL on PDW via RDW was also negative, indicating that the positive influence of SL on PDW can be moderated by its inverse association with root accumulation. Plant height (PH) had a small but positive indirect effect on root length, while RL exerted a negative indirect effect on PH, so these findings implied a compensatory relationship between aboveground and belowground growth: taller plants tend to promote root elongation slightly, whereas longer roots may limit aboveground height, potentially reflecting resource allocation trade-offs between shoots and roots. Internode distance, identified as a tertiary-order trait, indirectly affected PDW through its strong positive influence on PH and negative effect on RL. This indicated that DI can modulate PDW indirectly by shaping plant architecture, longer internodes favor taller plants but may constrain root growth, influencing the overall biomass accumulation. Leaflets per main stem, as a quaternary-order trait, indirectly affected PDW through its negative influence on DI, highlighting that foliar structure can regulate both internode development and, subsequently, plant height and yield. Thus, these

Table 7. The fitting indices for fitted model in path analysis

Cmin/df	NPAR	Cmin	DF	P	Cmin/df
	13	17.096	8	0.029	2.137
Comparative fit index (CFI)	δ1	ρ1	δ2	ρ2	CFI
	0.919	0.848	0.955	0.913	0.954
Comparative fit index (CFI)	P ratio	P NFI	P CFI		
	0.533	0.49	0.509		
Non-Centrality Parameter (NCP)	NCP	LO 90	HI 90		
	9.096	0.842	25.049		
Function Minimum	Fmin	F0	LO 90	HI 90	
	0.611	0.325	0.03	0.895	

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indirect pathways demonstrated the complex network of compensatory and synergistic relationships among morphological traits in summer savory. They emphasize that yield performance is not solely determined by primary traits like RDW and SL but also by how secondary, tertiary, and quaternary traits interact to shape plant architecture and resource allocation. Understanding these indirect effects allows breeders to select for trait combinations that optimize both shoot and root growth, ultimately enhancing plant dry weight under cool, upland, semi-arid conditions.

The path analysis revealed that stem length and root dry weight are primary-order traits that have a direct positive impact on plant dry weight performance. These findings were further validated using the bootstrapping method, confirming a significant association between plant dry weight and other morphological characteristics. Additionally, plant height and root length were identified as secondary-order traits, emphasizing their substantial influence on yield performance. The distance of internodes was categorized as a tertiary-order trait, while leaflets per main stem was identified as a quaternary-order trait, both of which were also linked to yield performance. These results provided valuable insights for genetic improvement programs aimed at enhancing the yield of summer savory under cool, upland, semi-arid conditions. By utilizing this knowledge, breeders can make informed decisions about which traits to prioritize in breeding programs to improve summer savory yield. The identified primary, secondary, tertiary, and quaternary-order traits serve as essential indicators to guide breeding efforts, helping to maximize yield potential for summer savory cultivation in these specific environmental settings.

Conflict of interest. There is no actual or potential conflict of interest in relation to this article.

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