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Path Analysis of Yield Components in Faba bean (*Vicia faba* L.) Across Supplementary Irrigation Regimes

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ABSTRACT

Background: Climate change threatens Mediterranean legume systems, with faba bean (*Vicia faba* L.) particularly vulnerable to water stress during key growth stages. While supplemental irrigation (SI) offers potential benefits, yield-trait relationships under different water regimes remain unclear. Path analysis, unlike simple correlations, separates direct and indirect effects, aiding in identifying traits that most influence yield.

Methods: A two-year (2020-2022) split-plot field trial at INRA-Douyet, Morocco, tested six faba bean genotypes under three irrigation regimes: rainfed (IR1), SI of 53 mm (IR2) and SI of 106 mm (IR3) at flowering. Traits measured included stems (NTS), pods (NP), seeds (NS), 100-seed weight (WSS) and plant yield (PY). Data were analyzed *via* combined ANOVA, Pearson correlations and path analysis.

Result: ANOVA showed significant effects of environment, genotype and their interaction. Yield was most sensitive to the environment, while WSS had the highest heritability. Path analysis revealed that WSS and NP had negative direct effects yet positive total correlations due to strong indirect influences, mainly through NP and NS. NS and NTS were generally unfavorable. The findings provide valuable insights for developing water-specific breeding strategies and optimizing agronomic practices in semi-arid Mediterranean environments.

Key words: Faba bean, Mediterranean climate, Path analysis, Supplementary irrigation, Trait selection, Yield components.

INTRODUCTION

Agriculture plays a strategic role in the Moroccan economy, contributing 12 to 14% of GDP and employing approximately 40% of the labor force (FAO, 2023). However, climate change has intensified water stress (WS) through rising temperatures, declining precipitation and more frequent droughts, leading to the longest dry period in recorded history (Bendidi *et al*., 2024; Ouraich and Tyner, 2018). Supplementary irrigation (SI) applying limited water during critical phenological stages has emerged as a key strategy to stabilize yields and improve stress tolerance (Zeleke and Nendel, 2019), making it a priority for Morocco's climate-smart agriculture (Bendidi *et al*., 2024).

Faba bean (*Vicia faba* L.) holds a prominent position in Mediterranean and semi-arid systems, offering nutritional benefits (high protein, fiber and micronutrients) and agronomic advantages (nitrogen fixation, soil improvement, rotational value) (Chetto *et al*., 2023). In consideration of its valuable nutritional qualities and climate adaptability, this important component of sustainable systems provides resilience in agricultural strategies and reformulation of diet (Nurmansyah *et al*., 2024). This crop occupies a significant place in intercropping systems (ICS) in Morocco. The most common combination for this farming practice is legumes/cereals (Tamta *et al*., 2019) or legumes/wheat (Chamkhi *et al*., 2022).

However, its productivity is highly sensitive to water deficits during flowering. Studies in semi-arid regions have shown SI benefits, including up to 52% increases in 1000-seed weight (Ouji *et al*., 2017) and notable yield improvements (Zeleke and Nendel, 2019). Yet varietal responses remain heterogeneous, requiring a better understanding of yield component interactions to inform breeding and agronomic decisions.

Classical correlation analysis identifies linear associations between traits (Sharma *et al*., 2021) but

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cannot differentiate direct from indirect effects, limiting insights into causal mechanisms (Hadi *et al*., 2023; Mbarek *et al*., 2013). Assessing how traits correlate is valuable for breeding program design; a positive correlation implies that increasing one trait will likely yield improvements in the other (Khomphet, 2024).

Path analysis, derived from structural equation modeling (SEM), addresses this by decomposing total effects into direct and indirect contributions, identifying the most determinant yield components (Chen *et al*., 2024; Gu *et al*., 2024; Wang *et al*., 2025). Osman *et al*. (2019) and Ambati *et al*. (2018) demonstrated that grain yield improvement requires selecting components based on correlation coefficients partitioned into direct and indirect effects, enabling precise trait targeting in breeding programs.

The present study aims to: (i) assess the impact of SI on the agronomic performance of six faba bean genotypes under semi-arid conditions and (ii) analyze yield component relationships using bivariate correlation and multivariate path analysis to identify key traits for improved varietal selection and optimized agronomic practices under future climatic scenarios.

MATERIALS AND METHODS

Trials were conducted at the National Institute of Agricultural Research (INRA-Douyet, Morocco), over two growing seasons: 2020-2021 (Y1) and 2021-2022 (Y2). The site (34°04′N, 5°07′W) is located in the Saïs plain, Province of Moulay Yaacoub, Fez-Meknes, at 416 m altitude. The climate is Mediterranean with a dry season from May to October.

Four major varieties (Hiba, Aguadulce, Extra hative, Defes) and two minor varieties (Zina, Alfia17) were tested. Manual seeding occurred on December 21, 2020 and December 14, 2021. The site was prepared by deep tillage with a three-disc plough, followed by cross-disc ploughing and disc pulverizing to refine the seedbed. The land had previously been rotated with cereals. Base fertilizer NPK “10-30-10” (200 kg/ha) was applied. Biotic agents were managed using commercial pesticides and cultural methods (mechanical hoeing) to prevent yield loss.

The experiment was designed as a split-plot with two replications. SI treatments (IR1, IR2 and IR3) were assigned to the main plots, while Faba bean varieties were assigned to subplots. Each elementary plot, measuring 21.6 m by 4 m, consisted of six rows per variety (36 rows per plot) with 0.60 m inter-row spacing. There were 3-meter-wide alleys between replicates and treatments. Each plot covered an area of 86.4 m^2 and the total experimental area was 811.8 m^2.

Three water treatments were applied (in a drip irrigation setting). The first (IR1) corresponded to the rainfed control with no water applied. The second (IR2) involved an application of 53 mm, equivalent to 31.8 liters per elementary plot or 3180 mL (per emitter spaced at 10 cm). The third (IR3) consisted of 106 mm of water, or 63.6 liters per plot, corresponding to 6360 mL (per emitter spaced at 20 cm). SI was applied only during the flowering stage, at 81 days after sowing (DAS) in the first year (Y1) and 127 DAS in the second year (Y2). The delay in Y2 was attributed to more constraining climatic conditions, particularly a 1.7°C increase in temperature and a 6.87 mm decrease in rainfall, which slowed the development of faba bean and postponed flowering. No irrigation was applied at any other growth stage. The applied volumes were distributed over several events at regular intervals (3 days) and were sufficient to maintain the arable soil layer at field capacity during this stage.

Measurements were carried out over two consecutive growing seasons, Y1 and Y2. Five healthy plants were randomly selected in the field for growth evaluations. These plant samples were manually harvested from the four central rows (out of six rows per variety), over a 0.5-meter length from the edge of each plot. Notably, all sampled plants were at the same physiological age, ensuring the uniformity of all measurements. Data collection was conducted for each treatment, variety and replicate. The plants used for yield analysis and their components were harvested on June 8, 2021 and June 15, 2022, corresponding to 87 days and 70 days, respectively, after the implementation of SI treatments during Y1 and Y2. The recorded yield components included NTS, NP, NS and WSS. To ensure the consistency and validity of the irrigation treatments, additional environmental parameters, including temperature, relative humidity and precipitation, were monitored throughout the experimental period using specialized software (FieldClimate, METOS® by Pessl Instruments, Austria).

Combined ANOVA was performed on pooled data (Y1, Y2) under IR1, IR2 and IR3 using PROC MIXED (SAS v.9.4). Irrigation regime, block within regime, variety and their interaction were fixed effects; replications were random. Mean squares significance was tested *via* F-tests. The percentage contribution (%SS) and broad-sense heritability (H^2) were computed as the ratio of genotypic to phenotypic variance. Genotypic Pearson correlations among traits (NTS, NP, NS, WSS, PY) per irrigation regime were calculated in R v.4.2.1 using ‘cor.test’ and visualized with ‘corrplot’.

The path-analysis model was constructed based on theoretical expectations and empirical relationships among yield components. Trait selection was guided by Pearson genetic correlations ($|r| > 0.3$, $P<0.05$), excluding traits with negligible associations to simplify the causal structure. All variables were standardized (mean = 0, SD = 1) for direct comparison of path coefficients. Multicollinearity was assessed *via* variance-inflation factors (VIF), removing or combining traits with VIF > 5 to stabilize estimates. The initial path diagram posited direct effects of NTS, NP, NS and WSS on PY, with indirect paths specified according to significant pairwise correlations. The model was fitted using maximum-likelihood estimation in the R package lavaan, consulting modification indices to identify missing pathways or remove non-significant links.

Iterative refinement continued until all paths were significant (P<0.05) and fit indices met thresholds. Path-coefficient analysis was performed separately for each irrigation regime, partitioning total genetic correlations into direct and indirect effects.

RESULTS AND DISCUSSION

Variation of faba bean traits under irrigation regimes

Combined analysis of variance for faba bean traits (NTS, NP, NS, WSS and PY) under different water regimes is summarized in Table 1.

Across environments and genotypes, highly significant differences were detected for most traits, indicating both the environment and genetic background contributed appreciably to total variation (Table 1). For NTS and NP, the environment accounted for 8.65% and 33.40% of the total SS, respectively, with mean squares that were significant at *P*<0.05 for NTS and at *P*<0.001 for NP. This shows that both NTS and NP are substantially influenced by the irrigation regime. In contrast, the environment had little influence on NS (1.26%, not significant) and a moderate but highly significant effect on WSS (22.18%, *P*<0.001) and PY (61.40%, *P*<0.001), indicating that environment plays a critical role in determining WSS and especially PY. The variety (genotype) source of variation was highly significant (*P*<0.001) for all five traits, explaining 12.40% of variation in NTS, 102.85% in NP, 154.20% in NS, 86.73% in WSS and 98.50% in PY. These large percentages reflect strong genetic divergence among the six faba bean varieties, particularly for NS and weight traits that were remarkably consistent across water regimes.

Genotype × environment interactions were significant for NTS (3.95%, *P*<0.05), NP (8.63%, *P*<0.01) and NS (6.85%, *P*<0.05), but not for WSS (1.92%, ns). The interaction was highly significant for PY (25.15%, *P*<0.001), showing that while certain varieties maintained stable stem and pod production across regimes, yield responses differed markedly depending on the water regime. Blocks within environments contributed minimally (2-8% of total variation) and were only significant for NP (5.82%, *P*<0.05) and PY (8.25%, *P*<0.05). Error variance ranged from 3.22% (WSS) to 21.70% (PY) and coefficients of variation show acceptable experimental precision (CV 6.44% for NP to 46.80% for PY). H^2 were moderate to high, from 58.6% for NTS up to 96.70% for WSS, indicating that selection for these traits, especially seed weight and seed number traits, should be effective under varying irrigation (Table 1). High H^2 estimates support their use as stable selection criteria, as reported in recent faba bean and legume studies (Esho and Salih, 2021; Hiywotu *et al*., 2023; Boukrouh *et al*., 2024).

Correlation and path analysis of agronomic traits in faba bean

Results revealed that under IR1, Faba bean yield was slightly correlated with NP, NS and WSS parameters (r = 0.10-0.36; *P*<0.05), indicating that optimizing these aspects would influence the overall yield. In contrast, strong correlations were spotted between WSS and both NP and NS (r = 0.7 to 0.75) (*P*<0.05). Furthermore, the transition from IR1 to the higher levels (IR2 and IR3) further affected these correlative effects. Regarding these conditions, the correlation between yield and faba bean parameters became stronger (r = 0.46-0.65; P<0.05), while the relationship between the variables NP, NS and WSS was weakened over the IR transition (r = 0.18-0.29; *P*<0.05) (Fig 1).

Path analysis revealed marked contrasts in the direct and indirect contributions of yield-related traits under different irrigation regimes (Table 2, Fig 2). Under IR1, WSS had a strong positive total effect on yield (+0.86) despite a large negative direct effect (-1.24), implying substantial positive indirect influence-mainly via NP and NS. NP showed a negative direct effect (-0.88) but a positive total correlation (+0.52), indicating its structural, indirect role. NS (-0.15 direct; -0.37 total) and NTS (-0.39) were essentially non-contributory. Under IR2, WSS again showed a strong positive total correlation (+0.75) despite a negative direct effect (-1.15). NP retained a negative direct effect

Table 1: Percentage sum of squares (%SS) and significance of mean squares from combined ANOVA for NTS, NP, NS, WSS and PY in faba bean under different irrigation regimes.

Source	df	Sum of squares (%SS)									
		NTS	sig	NP	sig	NS	sig	WSS	sig	PY	sig
Environment	1	8.65	*	33.4	***	1.26	ns	22.18	***	61.4	***
Block/Env	3	2.15	Ns	5.82	*	3.74	ns	1.95	ns	8.25	*
Variety	6	12.4	***	102.85	***	154.2	***	86.73	***	98.5	***
Var × Env	6	3.95	*	8.63	**	6.85	*	1.92	ns	25.15	***
Error	18	4.85		12.3		9.95		3.22		21.7	
Average		3.05		14.07		34.72		0.88		32.45	
CV (%)		37.05		6.44		9.52		11.89		46.8	
H^2		58.6		85.5		91.45		96.7		68.79	

*** = p<0.001; ** = p<0.01; * = p<0.05; ns= Not significant; df= Degree of freedom; H^2= Heritability; CV= Coefficient of variation; Var= Variety; NTS= Total number of stems; NP= Number of pods per plant; NS= Number of seeds per plant; WSS= Weight of 100 seeds; PY= Plant yield.

Table 2: Path coefficients (genetic correlation 'gc') of yield components influencing faba bean yield under different irrigation regimes (IR) at Douyet, Morocco (2020-2022).

Parameters	NTS	NP	NS	WSS	gc	IRs
NTS	(-0.39)	-0.74	0.45	0.29	0.13	IR1
	(-0.42)	-0.82	0.4	0.25	0.1	IR2
	(-0.35)	-0.65	0.5	0.35	0.25	IR3
NP	-0.53	(-0.88)	0.63	-0.24	0.52**	IR1
	-0.6	(-0.82)	0.7	-0.3	0.45*	IR2
	-0.45	(-0.92)	0.55	-0.18	0.4	IR3
NS	-0.06	0.8	(-0.15)	-0.42	-0.37	IR1
	-0.1	0.85	(-0.20)	-0.48	-0.4	IR2
	-0.02	0.75	(-0.10)	-0.35	-0.3	IR3
WSS	-0.44	-0.5	-0.37	(-1.24)	0.86**	IR1
	-0.5	-0.55	-0.42	(-1.15)	0.75**	IR2
	-0.38	-0.45	-0.32	(-1.3)	0.65**	IR3

Diagonal values represent direct effects on plant yield. Residual effect =-0.05 to -0.01; **= p<0.01; *= p<0.05.

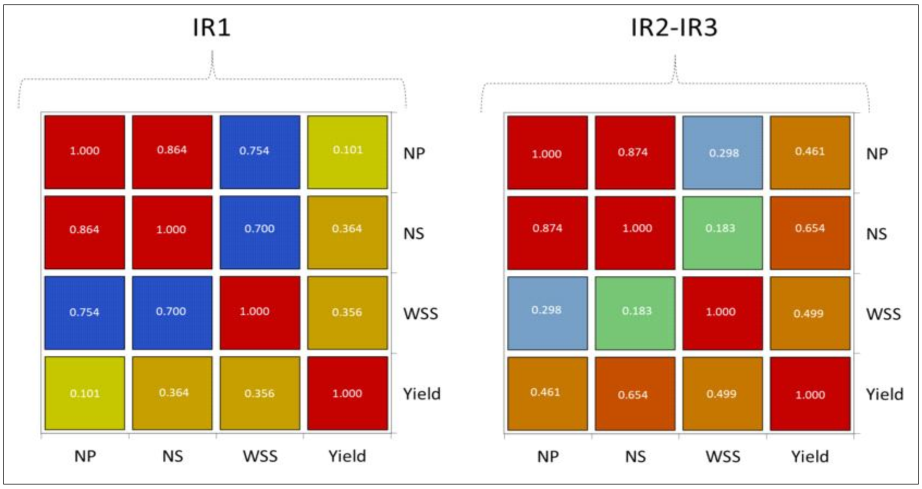

Fig 1: Correlation maps (Pearson type) displaying the relationship variations between faba bean predictive yield components under irrigation regimes.

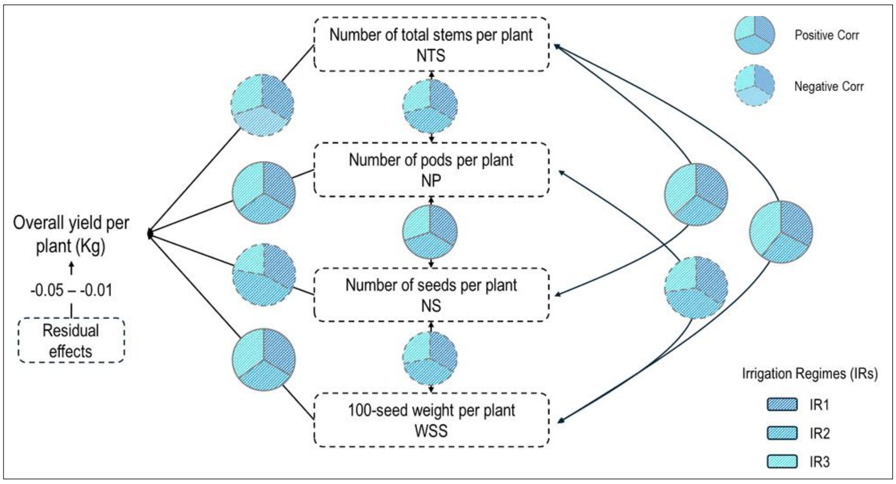

Fig 2: Path diagram showing direct effects on yield and correlation coefficients (represented in pie charts for each of the irrigation regimes) among the studied parameters of faba bean irrigated under different water regimes.

(-0.82) but a positive total (+0.45), reinforcing its indirect importance. NS (-0.20) remained a weak predictor and NTS continued to be unfavorable. Under IR3, WSS had its most negative direct effect (-1.30) yet kept a considerable total correlation (+0.65) *via* indirect pathways. NP continued to contribute indirectly (-0.92 direct; +0.40 total). NS (-0.10 direct; -0.30 total) remained of limited relevance, while NTS consistently showed negative effects across regimes.

NP acts as a central mediator: although its direct effect is negative, its consistent, strong indirect contribution across irrigation regimes, especially under moderate irrigation, makes it a valuable criterion for indirect selection. By contrast, NS shows persistently negative direct and total effects and is an unreliable yield predictor, particularly under water stress. NTS is broadly unfavorable, suggesting assimilate diversion to vegetative growth at the expense of reproductive organs.

To understand water influence on yield, correlation analysis was conducted between PY and the main agronomic components under different irrigation regimes. Under IR1, associations between PY and components (NP, NS, WSS) were low (r = 0.10-0.36) though significant (Fig 1), suggesting that under water stress, yield is influenced predominantly by external environmental factors (temperature, soil moisture, drought frequency) rather than morpho-productive traits (Dong *et al*., 2019). Liao *et al*. (2022) reported that soybean yield components are strongly influenced by environmental conditions, sometimes exceeding genetic factors. In contrast, Semcheddine and Hafsi (2014), found no correlation between cereal yield and grain number under rainfed conditions, while positive relationships appeared under controlled irrigation.

Conversely, under IR2 and IR3, the correlations between PY and NP, NS and WSS become more marked (r = 0.46-0.65) (Fig 1), indicating a better expression of the genetic potential of the genotypes. Increased water availability appears to favor the transfer of resources to reproductive structures, reinforcing the predictive value of morphological traits. These results corroborate those of Sharifi (2014) and Osman *et al*. (2019), who demonstrated that under favorable conditions, yield components are more reliable predictors of productivity. However, Dogan (2019) reported that irrigation water did not affect 1000-grain weight, highlighting the importance of genetic and environmental context.

One of the most remarkable results concerns WSS, which shows a strongly negative direct effect on yield in all regimes (from -1.24 to -1.30), while retaining a positive and significant overall correlation. This suggests an essentially indirect influence of WSS, notably *via* NP and NS. This apparent paradox illustrates the central role of WSS as a pivotal factor in yield construction, despite an unfavorable direct contribution. Similar observations were reported by Shferaw and Tarekegne (2024) and Hiywotu *et al*. (2023), who highlighted the importance of the indirect effects of biomass and harvest index *via* complex interactions. NP also emerges as an important mediating variable. Its negative direct effect is counterbalanced by a positive total correlation (up to +0.52), particularly under IR2, suggesting a relay role for the beneficial effects of WSS and NS. In contrast, NS shows consistently negative effects (direct and total), disqualifying it as a priority selection criterion in semi-arid Morocco. Ouji *et al*. (2017) demonstrated that under water stress, components like NS or WSS can be strongly affected, compromising their stability as indicators.

CONCLUSION

This study highlights the complexity of yield determinants in *V. faba* depending on the water regime applied. The correlations observed between NP, NS, WSS and yield varied significantly according to SI. Under IR1, these relationships are weak, reflecting the major influence of environmental factors. On the other hand, under IR2, IR3, the correlations become stronger, reflecting a better expression of the genetic potential of the genotypes. The path analysis confirmed the structuring role of WSS, which, despite a negative direct effect, contributes positively to yield via powerful indirect effects, in particular through NP and NS. NP, although marked by a negative direct effect, plays an indirect pivotal role, particularly under IR2. Conversely, NS and NTS appear to be unreliable criteria, with overall negative contributions. These results highlight the need for differentiated selection by water regime: WSS and NP serve as key indirect criteria under irrigation, while rainfed systems require more plastic traits. This crossover approach provides a relevant framework for varietal selection in semi-arid zones facing current climatic challenges.

Conflict of interest

The authors declare that they have no conflict of interest.

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