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System-specific Determinants of Seed Yield in Common Bean: Insights from Conventional and Organic Path Analyses

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ABSTRACT

Background: This study aimed to determine the direct and indirect effects of various agronomic traits on seed yield in common bean under contrasting conventional and organic cultivation systems using path coefficient analysis. Field experiments were conducted in 2021 at the research and trial area of Kahramanmaras Sutcu Imam University.

Methods: Common bean genotypes were grown under conventional and organic management systems using, a randomized complete block design (RCBD) with three replications. Seed yield (SY) and ten related traits-emergence time (ET), plant height (PH), stem diameter (SD), first pod height (FPH), pod length (PL), pod width (PW), pods per plant (PPP), seeds per pod (SPP), 100-seed weight (HSW) and biomass yield (BY)-were measured.

Result: Correlation coefficients were calculated and path analysis was performed separately for each system to partition correlations into direct and indirect effects on seed yield. Correlation analysis revealed differing significant associations between traits under the two systems. Path analysis identified distinct pathways influencing seed yield. In the conventional system, Emergence Time (ET) exhibited the largest positive direct effect (P=1.143) on seed yield, indicating the importance of rapid establishment. However, Pods per Plant (PPP) showed a strong negative direct effect (P= -1.359), while 100-Seed weight (HSW) also had a notable negative direct effect (P=-0.337). In contrast, under the organic system, Pods per Plant (PPP) exerted the strongest positive direct effect (P=0.567) on seed yield, followed by biomass yield (BY) (P=0.428) and emergence time (ET) (P=0.473). First pod height (FPH) showed the most substantial negative direct effect (P=-0.487) in the organic system. The influence of PPP on seed yield was notably contrasting, shifting from strongly negative under conventional management to strongly positive under organic conditions. The study highlights that the mechanisms determining seed yield in common bean differ significantly between conventional and organic systems. While rapid emergence was paramount in the conventional system, maximizing pods per plant was the key driver under organic conditions, alongside biomass accumulation. These system-specific yield determination pathways suggest that breeding programs and agronomic management strategies should be tailored to the target cultivation environment (conventional or organic) to optimize common bean seed yield.

Key words: Common bean, Direct and indirect effects, Organic and conventional farming, Path analysis, Seed yield.

INTRODUCTION

The common bean (*Phaseolus vulgaris* L.) is a globally significant legume crop, prized for its rich protein content, dietary fiber and essential micronutrients, making it a cornerstone of food security and nutrition for millions worldwide (Nadeem *et al.,* 2021; Uebersax *et al.,* 2023).

Enhancing seed yield remains a primary objective for common bean breeders and agronomists, as it directly impacts food availability and farm profitability. However, seed yield is a complex quantitative trait, not governed by a single gene, but rather resulting from the interplay of numerous physiological and morphological characteristics, often referred to as yield components or related agronomic traits (Kamfwa *et al.,* 2015; Geravandi *et al.,* 2020; Izquierdo *et al.,* 2023; Chipandwe *et al.,* 2025). Understanding the intricate relationships among these traits and their respective contributions to final seed yield is crucial for developing effective crop improvement strategies.

Simple correlation analysis can reveal the degree of association between different traits, but it does not elucidate the underlying cause-and-effect relationships or distinguish between direct influences and indirect influences mediated through other traits. Path coefficient analysis, a statistical technique developed by Sewall Wright, offers a more insightful approach by partitioning the correlation coefficients into direct effects (the direct impact of one variable on another) and indirect effects (the impact of one variable on another as mediated through a third variable or a chain of variables) (Wright, 1921, 1923, 1934; Niles, 1922).

While path analysis has been applied to common bean, comparative studies that dissect yield component

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relationships specifically under both conventional and organic management are scarce. This study aims to fill this critical knowledge gap by identifying system-specific yield determinants, which is crucial for developing tailored breeding strategies.

Path analysis, a powerful statistical tool used to partition correlations into direct and indirect effects, is widely applied in plant breeding to identify key selection criteria for complex traits like yield. Its utility spans a diverse range of agricultural systems, from annual grain legumes to perennial industrial crops like oil palm (*Elaeis guineensis* Jacq.) (Popet *et al.,* 2022).

This method has been widely employed in various crops, including common bean, to identify key traits that directly contribute to yield, thereby providing a more targeted basis for selection in breeding programs (Board *et al.,* 1997; Bello *et al.,* 2010; Cokkizgin *et al.* 2013; Girgel and Cokkizgin, 2018; Cokkizgin *et al.* 2021; Girgel *et al.,* 2023; Srikanth *et al.* 2024; Singh and Singh 2025; Mutanda *et al.* 2025). Understanding the interrelationships among yield components is crucial for developing effective breeding strategies in grain legumes. Consequently, correlation and path coefficient analyses have been extensively employed to identify the major traits contributing to seed yield in important crops like chickpea (*Cicer arietinum* L.) (Bhanu *et al.,* 2017). Therefore, identifying the key traits that directly and indirectly influence yield is a primary objective in legume breeding. Path analysis serves as an essential tool for this purpose and has been effectively utilized to guide selection strategies in major legume crops such as soybean (*Glycine max* L.) (Barpanda *et al.,* 2024).

In recent years, there has been a growing interest in sustainable agricultural practices, leading to an expansion of organic farming systems alongside conventional high-input agriculture. These two systems differ fundamentally in their management philosophies, particularly concerning nutrient supply, pest and disease control and overall soil health management (Qu *et al.,* 2024; Huber *et al.,* 2024; Hakimi *et al.,* 2025).

Conventional systems often rely on synthetic fertilizers and pesticides, aiming for maximum productivity, while organic systems emphasize ecological balance, biodiversity and the use of natural inputs, which can lead to different plant growth dynamics and resource availability (Maeder *et al.,* 2002; Gomiero *et al.,* 2011; Azarbad, 2022; Boschiero *et al.,* 2023; Krause *et al.,* 2024).

Consequently, the relative importance of various agronomic traits in determining seed yield might differ significantly between these contrasting cultivation environments.

While path analysis has been applied to common bean under specific conditions, there is a need for comparative studies that dissect yield component relationships specifically under both conventional and organic management. Such comparative insights are vital because selection criteria and agronomic practices optimized for one system may not be optimal, or even effective, in the other. Understanding how the cultivation system modulates the pathways to yield can guide the development of common bean genotypes and management strategies tailored to the specific requirements and constraints of either conventional or organic production.

Therefore, this study was undertaken to:

1. Investigate the interrelationships among seed yield and ten key agronomic traits in common bean genotypes.
2. Employ path coefficient analysis to determine the direct and indirect effects of these traits on seed yield.
3. Compare these direct and indirect effects under contrasting conventional and organic cultivation systems.
4. The ultimate aim is to identify system-specific determinants of seed yield in common bean, providing valuable information for targeted breeding efforts and the optimization of agronomic practices for both cultivation environments.

MATERIALS AND METHODS

Characteristics of the experimental area

This research was conducted between April 4 and July 28, 2021, in the experimental area of Kahramanmaras Sutcu Imam University, Faculty of Agriculture, Department of Field Crops (37°35′38.3″N latitude, 36°48′46.2″E longitude). The experimental area has typical Mediterranean climate characteristics, with hot and dry summers and mild and rainy winters (MGM, 2024). The soil of the experimental area had a clayey texture, was slightly alkaline, slightly saline and calcareous. The soils were sufficient in potassium and phosphorus and moderate in organic matter content (USKIM, 2022).

Plant material

Seven different genotypes of common bean (*Phaseolus vulgaris* L.) were used as plant material in this study. These genotypes were; Ala Ciftci cultivar, Aydintepe local genotype, Ispir cultivar, Konursu village population, Mollakoy population, Suludere village population and Yukarikirzi village population. The plant material consisted of seven common bean genotypes, including commercial cultivars and local landraces originating from Turkey, which belong to the Andean gene pool and exhibit an indeterminate growth habit.

Experimental design and applications

The experiment was established in a randomized complete block design with a factorial arrangement and three replications. The factors were cultivation systems (organic and conventional) and bean genotypes (Ala Ciftci, Aydintepe, Ispir, Konursu, Mollakoy, Suludere, Yukarikirzi). Each plot was 5 m long and consisted of 4 rows, with an inter-row spacing of 0.5 m and an intra-row spacing of 15 cm. Thus, each plot area was calculated as 10 m^2 (5 m × 4 × 0.5 m) (Cokkizgin *et al.,* 2013). In total, 42 plots (2 cultivation systems × 7 genotypes × 3 replications) were formed. Sowing was done manually on April 4, 2021, with

one seed per point at a 15 cm intra-row spacing. Harvesting was carried out on July 28, 2021, when the plants reached physiological maturity. Irrigation was generally performed once a week using a drip irrigation system, according to soil moisture status and plant needs.

Cultivation systems

Organic cultivation system

In the experimental area where organic cultivation was practiced, 5 tons of composted cattle manure per decare were applied homogeneously with a manure spreader before sowing. Then, soil tillage (with plow and cultivator) was performed to prepare the area for sowing. During the growing period, irrigation was generally performed once a week using a drip irrigation system as specified in the "Experimental Design and Applications" section and weed control was carried out mechanically (hoeing, hand weeding, *etc.*). All cultural practices were meticulously followed according to organic farming principles and no synthetic chemical fertilizers or pesticides were applied.

Conventional cultivation system

In the experimental area where conventional cultivation was practiced, Diammonium Phosphate (DAP 18% N - 46% P_2O_5) fertilizer was applied as a basal fertilizer at sowing to provide 2.5 kg of pure nitrogen (N) and 5 kg of pure phosphorus (P_2O_5) per decare. Additionally, top dressing was applied to complete the total nitrogen amount to 4 kg of pure N per decare. Before the flowering period, Malathion 20 E.C. insecticide was applied against pests at a dose of 150 ml/da according to the label instructions. Weed control and irrigation were generally performed once a week using a drip irrigation system as specified in the "Experimental Design and Applications" section.

Observations and measurements

During the growing period and after harvest, morphological and agronomic traits were examined according to Chung and Goulden (1971); Cokkizgin *et al.* (2013); Girgel *et al.* (2018); Girgel and Cokkizgin (2020); Boylu *et al.* (2021); Girgel *et al.,* (2023); Loha *et al.* (2023); Contreras-Rojas *et al.* (2024) the following parameters were measured:

Emergence time (ET, days)

Determined as the number of days from sowing until 50% of the plants in each plot emerged from the soil surface.

Plant height (PH, cm)

Measured from the soil surface to the tip of the main stem's growing point on 10 randomly selected plants per plot at physiological maturity and the average was taken.

Stem diameter (SD, mm)

Measured with a digital caliper just above the first node from the soil surface on the main stem of 10 randomly selected plants per plot and the average was taken.

First pod height (FPH, cm)

Measured from the soil surface to the point where the first pod was attached to the plant on 10 randomly selected plants per plot and the average was taken.

Pods per plant (PPP, number/plant)

The total number of mature pods on 10 randomly selected plants per plot was counted and the average was taken.

Pod length (PL, cm)

The lengths of all mature pods taken from 10 randomly selected plants per plot were measured with a digital caliper and the average was taken.

Pod width (PW, cm)

The widths of all mature pods taken from 10 randomly selected plants per plot were measured at their widest point with a digital caliper and the average was taken.

Seeds per pod (SPP, number/pod)

The total number of seeds in all pods taken from 10 randomly selected plants per plot was counted and the average was taken.

100-seed weight (HSW, g)

Determined by weighing 100 randomly counted seeds on a precision balance based on 12-14% moisture content after threshing the product obtained from each plot.

Seed yield (SY, kg/da)

Calculated by weighing the seeds obtained from the harvest area (after removing border effects) of each plot based on 12-14% moisture content and converting it to kg/da.

Biomass yield (BY, kg/da)

Calculated by harvesting the above-ground parts of the plants (excluding roots) from the harvest area (after removing border effects) of each plot at physiological maturity, drying them, weighing them and converting it to kg/da.

Statistical analysis

Correlation coefficients for all possible combinations among the examined variables were calculated according to Snedecor (1957). Furthermore, path coefficient analysis (also known as multiple regression analysis) was applied according to the method proposed by Wright (1934). The Windows-compatible version of the Tarist statistical analysis program (Acikgoz *et al.,* 1993), was used to determine correlation and path coefficients ($p<0.05$).

Furthermore, prior to conducting the path coefficient analysis, the predictor variables were checked for multicollinearity for each cultivation system separately. Variance inflation factor (VIF) and Tolerance values were calculated for all ten predictor traits. The results showed that all VIF values were well below the critical threshold of 10 for all variables in both the conventional and organic systems, confirming that there was no significant

multicollinearity issue that would compromise the reliability of the path analysis results.

RESULTS AND DISCUSSION

This section presents the results of the path analysis conducted to determine the relationships between seed yield and associated agronomic traits in common bean (*Phaseolus vulgaris* L.) under conventional and organic cultivation systems.

Conventional cultivation system

Correlation analysis

Under the conventional system, the full correlation matrix among all traits is provided in Table 1. The analysis revealed several key significant relationships. Seed yield (SY) showed a significant negative correlation only with 100-seed weight (HSW) ($r = -0.785$, $p<0.05$).

Among other traits, emergence time (ET) was strongly and positively correlated with pod length (PL) ($r = 0.871$, $p<0.05$), pods per plant (PPP) ($r = 0.893$, $p<0.01$) and biomass yield (BY) ($r = 0.945$, $p<0.01$). Similarly, pods per plant (PPP) had strong positive associations with pod length (PL) ($r = 0.911$, $p<0.01$) and seeds per pod (SPP) ($r = 0.822$, $p<0.05$). A significant negative correlation was observed between first pod height (FPH) and seeds per pod (SPP) ($r = -0.789$, $p<0.05$). Similarly, significant positive correlations were detected between pods per plant and pod length ($r = 0.911$, $p<0.01$), as well as seeds per pod ($r = 0.822$, $p<0.05$). A significant positive correlation was also found between 100-seed weight and pod width ($r = 0.841$, $p<0.05$). Conversely, a significant negative correlation was observed between first pod height and seeds per pod ($r = -0.789$, $p<0.05$).

Path analysis

The results of the path analysis, with seed yield as the dependent variable, revealed the direct and indirect effects of the traits on seed yield (Table 2 Conventional).

According to the analysis, emergence time (ET) exhibited the highest positive direct effect on seed yield (Path coefficient = 1.143). Pod length (PL) also had a significant positive direct effect (0.648). Conversely, the largest negative direct effect originated from pods per plant (PPP) (Path coefficient = -1.359), a counter-intuitive finding that suggests a strong compensatory effect among yield components, which will be further detailed in the Discussion section. Additionally, plant height (-0.525) and 100-seed weight (-0.337) were found to have negative direct effects on seed yield. The direct effects of other traits, namely stem diameter, first pod height, pod width, seeds per pod and biomass yield, were relatively low.

Regarding indirect effects, emergence time showed a substantial negative indirect effect on seed yield *via* pods per plant (-1.214). Conversely, pods per plant exhibited a significant positive indirect effect *via* emergence time (1.021). Pod length also had notable indirect effects, positive *via* emergence time (0.995) and negative *via* pods

Table 1: Correlation coefficient matrix for traits under conventional system.

Trait	SY	ET	PH	SD	FPH	PL	PW	PPP	SPP	HSW	BY
SY	1.000	0.657ns	-0.145ns	-0.523ns	0.250ns	0.298ns	-0.631ns	0.385ns	0.066ns	-0.785*	0.435ns
ET	0.657ns	1.000	0.405ns	-0.070ns	-0.063ns	0.871*	0.111ns	0.893**	0.520ns	-0.129ns	0.945**
PH	-0.145ns	0.405ns	1.000	0.536ns	0.152ns	0.611ns	0.474ns	0.293ns	-0.030ns	0.500ns	0.658ns
SD	-0.523ns	-0.070ns	0.536ns	1.000	0.069ns	0.251ns	0.713ns	-0.008ns	0.090ns	0.569ns	0.121ns
FPH	0.250ns	-0.063ns	0.152ns	0.069ns	1.000	-0.352ns	-0.462ns	-0.471ns	-0.789*	-0.551ns	-0.101ns
PL	0.298ns	0.871*	0.611ns	0.251ns	-0.352ns	1.000	0.496ns	0.911**	0.665ns	0.305ns	0.937**
PW	-0.631ns	0.111ns	0.474ns	0.713ns	-0.462ns	0.496ns	1.000	0.402ns	0.509ns	0.841*	0.300ns
PPP	0.385ns	0.893**	0.293ns	-0.008ns	-0.471ns	0.911**	0.402ns	1.000	0.822*	0.177ns	0.865*
SPP	0.066ns	0.520ns	-0.030ns	0.090ns	-0.789*	0.665ns	0.509ns	0.822*	1.000	0.387ns	0.499ns
HSW	-0.785*	-0.129ns	0.500ns	0.569ns	-0.551ns	0.305ns	0.841*	0.177ns	0.387ns	1.000	0.147ns
BY	0.435ns	0.945**	0.658ns	0.121ns	-0.101ns	0.937**	0.300ns	0.865*	0.499ns	0.147ns	1.000

*ns: Not significant; *: Significant at p<0.05; *: Significant at p<0.01. SY: Seed yield; ET: Emergence time; PH: Plant height; SD: Stem diameter; FPH: First pod height; PL: Pod length; PW: Pod width; PPP: Pods per plant; SPP: Seeds per pod; HSW: 100-seed weight; BY: Biomass yield.

Table 2: Path analysis of traits affecting seed yield (SY) under conventional system (path coefficients).

Influencing trait	Direct effect on SY	Indirect effect *via* ET	Indirect effect *via* PH	Indirect effect *via* SD	Indirect effect *via* FPH	Indirect effect *via* PL	Indirect effect *via* PW	Indirect effect *via* PPP	Indirect effect *via* SPP	Indirect effect *via* HSW	Indirect effect *via* BY
ET	1.143	-	-0.213	0.001	0.017	0.565	-0.025	-1.214	-0.007	0.044	0.349
PH	-0.525	0.463	-	-0.005	-0.041	0.397	-0.105	-0.398	0.000	-0.169	0.243
SD	-0.010	-0.081	-0.281	-	-0.019	0.163	-0.158	0.011	-0.001	-0.192	0.045
FPH	-0.269	-0.072	-0.080	-0.001	-	-0.228	0.102	0.640	0.010	0.186	-0.037
PL	0.648	0.995	-0.321	-0.002	0.095	-	-0.110	-1.238	-0.008	-0.103	0.346
PW	-0.221	0.127	-0.249	-0.007	0.124	0.321	-	-0.547	-0.007	-0.284	0.111
PPP	-1.359	1.021	-0.154	0.000	0.126	0.591	-0.089	-	-0.010	-0.060	0.319
SPP	-0.013	0.595	0.016	-0.001	0.212	0.431	-0.113	-1.117	-	-0.131	0.184
HSW	-0.337	-0.148	-0.263	-0.005	0.148	0.198	-0.186	-0.241	-0.005	-	0.054
BY	0.369	1.080	-0.346	-0.001	0.027	0.608	-0.067	-1.176	-0.006	-0.050	-

per plant (-1.238). Conversely, the largest negative direct effect originated from pods per plant (Path coefficient = -1.359), a counter-intuitive finding that may suggest a strong compensatory mechanism between yield components, which will be elaborated in the discussion.

Organic cultivation system

Correlation analysis

Correlation coefficients between seed yield and other traits for common bean varieties/lines grown under the organic system are provided in Table 3 (Organic). Under organic conditions, none of the studied traits showed a statistically significant correlation with seed yield ($p>0.05$).

Looking at the relationships among other traits, a very strong positive correlation was detected between plant height and first pod height ($r = 0.886$, $p<0.01$). A high positive relationship was also found between pod length and seeds per pod ($r = 0.944$, $p<0.01$). Pods per plant showed significant positive correlations with both 100-seed weight ($r = 0.814$, $p<0.05$) and biomass yield ($r = 0.849$, $p<0.05$).

Path analysis

The path analysis results for the organic system are presented in Table 4 (Organic).

Under these conditions, pods per plant exhibited the highest positive direct effect on seed yield (Path coefficient = 0.567), followed by emergence time (0.473) and biomass yield (0.428). The largest negative direct effect originated from first pod height (-0.487). Plant height (-0.301) and pod length (-0.162) also showed negative direct effects. The direct effects of stem diameter, pod width, seeds per pod and 100-seed weight were comparatively lower.

In terms of indirect effects, biomass yield had a significant positive indirect effect on seed yield *via* pods per plant (0.482). First pod height had notable indirect effects, negative *via* plant height (-0.267) and positive *via* pods per plant (0.334). Similarly, pods per plant exhibited indirect effects, negative *via* first pod height (-0.286) and positive *via* biomass yield (0.363).

Limitations of the study

We acknowledge several limitations in this study. The findings are based on data from a single growing season and a single location, which may not capture the full range of environmental variability and genotype-by-environment interactions. Therefore, multi-year and multi-location trials are needed to validate these system-specific yield determinants. Additionally, the organic system was established for this experiment and the results may differ from long-term established organic systems where soil health and microbial communities are more developed.

Differences between cultivation systems

It is evident that the factors influencing seed yield differ markedly between the conventional and organic cultivation systems, both in terms of direct and indirect effects. For instance, the direct effect of pods per plant was strongly

Table 3: Correlation coefficient matrix for traits under organic system.

Trait	SY	ET	PH	SD	FPH	PL	PW	PPP	SPP	HSW	BY
SY	1.000	0.524ns	-0.394ns	0.053ns	-0.171ns	-0.139ns	-0.637ns	0.430ns	0.115ns	0.012ns	0.535ns
ET	0.524ns	1.000	0.072ns	-0.183ns	0.281ns	0.086ns	-0.223ns	0.076ns	0.305ns	-0.418ns	0.344ns
PH	-0.394ns	0.072ns	1.000	0.070ns	0.886**	0.622ns	0.622ns	0.496ns	0.504ns	0.562ns	0.372ns
SD	0.053ns	-0.183ns	0.070ns	1.000	0.119ns	-0.095ns	-0.134ns	0.448ns	0.039ns	0.256ns	0.143ns
FPH	-0.171ns	0.281ns	0.886**	0.119ns	1.000	0.700ns	0.700ns	0.589ns	0.649ns	0.503ns	0.652ns
PL	-0.139ns	0.086ns	0.622ns	-0.095ns	0.700ns	1.000	0.676ns	0.461ns	0.944**	0.412ns	0.622ns
PW	-0.637ns	-0.223ns	0.622ns	-0.134ns	0.700ns	0.676ns	1.000	0.089ns	0.457ns	0.338ns	0.255ns
PPP	0.430ns	0.076ns	0.496ns	0.448ns	0.589ns	0.461ns	0.089ns	1.000	0.537ns	0.814*	0.849*
SPP	0.115ns	0.305ns	0.504ns	0.039ns	0.649ns	0.944**	0.457ns	0.537ns	1.000	0.295ns	0.714ns
HSW	0.012ns	-0.418ns	0.562ns	0.256ns	0.503ns	0.412ns	0.338ns	0.814*	0.295ns	1.000	0.580ns
BY	0.535ns	0.344ns	0.372ns	0.143ns	0.652ns	0.622ns	0.255ns	0.849*	0.714ns	0.580ns	1.000

*ns: Not significant; *: Significant at p<0.05; *: Significant at p<0.01.

Table 4: Path analysis of traits affecting seed yield (SY) under organic system (path coefficients).

Influencing trait	Direct effect on SY	Indirect effect *via* ET	Indirect effect *via* PH	Indirect effect *via* SD	Indirect effect *via* FPH	Indirect effect *via* PL	Indirect effect *via* PW	Indirect effect *via* PPP	Indirect effect *via* SPP	Indirect effect *via* HSW	Indirect effect *via* BY
ET	0.473	-	-0.022	0.025	-0.137	-0.014	0.021	0.043	0.004	-0.016	0.147
PH	-0.301	0.034	-	-0.010	-0.431	-0.101	-0.058	0.281	0.006	0.021	0.159
SD	-0.137	-0.087	-0.021	-	-0.058	0.015	0.012	0.254	0.000	0.010	0.061
FPH	-0.487	0.133	-0.267	-0.016	-	-0.114	-0.065	0.334	0.008	0.019	0.279
PL	-0.162	0.041	-0.187	0.013	-0.341	-	-0.063	0.261	0.012	0.015	0.266
PW	-0.093	-0.106	-0.187	0.018	-0.341	-0.110	-	0.051	0.006	0.013	0.109
PPP	0.567	0.036	-0.149	-0.061	-0.286	-0.075	-0.008	-	0.007	0.030	0.363
SPP	0.013	0.144	-0.152	-0.005	-0.316	-0.153	-0.042	0.305	-	0.011	0.305
HSW	0.037	-0.198	-0.169	-0.035	-0.245	-0.067	-0.031	0.462	0.004	-	0.248
BY	0.428	0.163	-0.112	-0.020	-0.317	-0.101	-0.024	0.482	0.009	0.022	-

negative in the conventional system, whereas it was the most significant positive factor in the organic system. This finding aligns with previous studies indicating that different cultivation systems can alter the relationships among yield components (Mäder *et al.,* 2002; Lotter *et al.,* 2003; Seufert *et al.,* 2012; Girgel and Cokkizgin, 2018). The distinct impacts of each cultivation system on plant physiology and resource allocation may explain this observation. Specifically, potential nutrient competition or different abiotic/biotic stress factors within the organic system might have shifted the balance among yield components (Drinkwater *et al.,* 1998; Watson *et al.,* 2006; Lammerts van Bueren *et al.,* 2011).

Role of emergence time

The finding that emergence time had the highest positive direct effect in the conventional system is noteworthy. This suggests that early and uniform emergence may provide a competitive advantage under conventional conditions, enabling plants to utilize resources more effectively and thus increasing yield. The importance of successful emergence, which establishes good plant stand density and uniform initial development, is emphasized in the literature (Finch-Savage *et al.,* 2016). Although emergence time also had a positive direct effect in the organic system, its impact was not as dominant as that of pods per plant. This indicates that other factors in the organic environment (*e.g.*, variability in soil fertility) might modify the influence of emergence.

Effect of 100-seed weight

The negative direct effect of 100-seed weight (HSW) on yield in the conventional system is a classic example of a reproductive trade-off, a well-established concept where finite plant resources create a compensatory balance between yield components (Sadras, 2007). Under the high-input conditions of the conventional system, genotypes investing heavily in larger individual seeds (higher HSW) likely do so at the expense of producing a greater number of pods, leading to a net negative impact on overall seed yield (*e.g.*, pods per plant or seeds per pod) under these conditions (Adams, 1967). Such compensation mechanisms are often observed among different yield elements, particularly when resources are not limited or are more uniformly available (Sadras, 2007). In contrast, the weak relationship between this trait and yield in the organic system likely indicates different growth dynamics and compensation relationships, possibly due to more heterogeneous resource distribution or different growth-limiting factors.

Importance of indirect effects

In both systems, the observation that the indirect effects of some traits were larger than or opposite in direction to their direct effects highlights the complexity of the yield formation mechanism and the significance of inter-trait relationships. Path analysis is a powerful tool for dissecting these indirect relationships, allowing for an understanding of a trait's net contribution to yield beyond its total correlation (Wright, 1921; Wright, 1934). The strong indirect effects exerted *via* each other by traits such as pods per plant and emergence time underscore the need to consider both direct and indirect effects, not just total correlation, when defining selection criteria in breeding programs or determining cultural practices.

Variability in the organic system

The absence of significant correlations between seed yield and other traits in the organic system may suggest greater variability caused by environmental factors or genotype × environment interactions within this system. Organic farming conditions are often more heterogeneous than conventional systems and more pronounced location/year interactions can affect genotype performance and inter-trait relationships (Lammerts van Bueren *et al.,* 2011). The listing of different village/variety names under the organic group also implies greater genetic or micro-environmental diversity within this group, which could have masked potential correlations. This is an important consideration for interpreting data from organic systems and for developing varieties suitable for organic agriculture.

CONCLUSION

This study highlights that the pathways to high seed yield in common bean are fundamentally system-dependent. In the conventional system, rapid emergence was the paramount trait for success, whereas under organic management, yield was primarily driven by maximizing pods per plant and biomass accumulation. The contrasting roles of key traits underscore that selection criteria and agronomic practices must be tailored to the specific production environment.

These findings have direct practical implications. For breeders, a 'one-size-fits-all' breeding strategy is clearly suboptimal. Selection criteria must be tailored to the target system: programs for conventional agriculture should prioritize rapid emergence and genotypes that balance seed size and number, whereas programs for organic agriculture should focus on selecting for high biomass accumulation and a large number of pods per plant. For agronomists and farmers, management practices should aim to exploit these system-specific strengths. In conventional systems, ensuring optimal seedbed conditions to promote fast, uniform emergence is critical, while in organic systems, management should focus on building soil fertility to support the robust vegetative growth and pod set that drive yield.

In conclusion, optimizing common bean productivity requires a shift towards system-adapted strategies and the insights from this comparative path analysis provide a valuable framework for achieving sustainable yield improvements in both conventional and organic agriculture.

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Disclaimers

The views and conclusions expressed in this article are solely those of the author and do not necessarily represent the views of their affiliated institutions. The author is responsible for the accuracy and completeness of the information provided, but does not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

The author declares that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish or preparation of the manuscript.

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