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Optimal Yield Related Attributes for High Grain Yield using Ontogeny Based Sequential Path Analysis in Barnyard Millet (*Echinochloa spp.*)

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ABSTRACT

Relationship between grain yield and its component traits can improve the efficiency of breeding programs by determining appropriate selection criteria. An investigation was carried out on barnyard millet (*Echinochloa* spp.) global germplasm collection to investigate the association among yield components and their direct and indirect effects on the grain yield of barnyard millet. The experiment was conducted in 2011 and 2012 in augmented and alpha lattice design, respectively. The results of correlation coefficients indicated that grain yield had high significant and positive association with flag leaf width and culm thickness during both years, whereas negative association of grain yield was observed with basal tillers and peduncle length. Simple path analysis indicated high direct effects of panicle exertion, flag leaf sheath length, flag leaf width and days to maturity in 2011; and flag leaf width and raceme number in 2012. However, these high direct estimates were biased due to multicolinearity. Therefore, ontogeny based sequential path analysis was used to establish the causal relationships determining grain yield in barnyard millet. Based on the results over the years, culm thickness and raceme number were found to be important traits for indirect selection. The other important traits suggested for inclusion in selection index were inflorescence length, plant height, flag leaf length, inflorescence width and number of basal tillers per plant.

Keywords: Causal relationship, Correlation, Multicolinearity, Predictor variables, Structural Equation Modelling.

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INTRODUCTION

Barnyard millet (*Echinochloa* spp.) is potential food and fodder crop in the semi-arid tropics of Asia and Africa. It is mainly cultivated in India, Japan and China as a subsistence crop in marginal areas (Sood *et al*., 2015). The two main cultivated species of the crop are *E. esculenta* (A. Braun) H. Scholz; syn. *E. utilis* Ohwi et Yabuno (Japanese Barnyard millet) *and E. frumentacea* Link; syn. *E. colona* var *frumentacea* (Link) Ridl. (Indian Barnyard millet) (Sood *et al*., 2014). It is mainly cultivated in areas where climatic and edaphic conditions are unsuitable for rice cultivation (Yabuno, 1987). In India, barnyard millet is grown from Himalayan region in the north to Deccan plateau in the south. It is generally cultivated in hill slopes and undulating fields of hilly, tribal or backward areas, where few options exist for crop diversification. It is a short duration, fast growing hardy crop and has been identified as one of the climate resilient crops (Padulosi *et al*., 2009). The crop is gaining popularity due to its rich nutritional profile along with high dietary fibre content, lack of gluten and use as functional food.

Grain yield is a quantitative trait and highly affected by environmental factors. Plant breeders commonly prefer yield components

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that indirectly increase seed yield. Correlation of a particular character with other characters contributing to grain yield is of great importance in indirect selection of genotypes for higher grain yield. Simple Pearson correlations merely look at how two traits change together and may not provide a complete understanding about the importance of each component in determining grain yield (Dewey and Lu, 1959). Path coefficient analysis has been widely used in plant breeding programs to determine the nature of the relationships between yield and yield components that are useful as selection criteria to improve crop yield. In most studies involving path analysis, researchers considered the predictor characters as first-order variables in order to analyze their effects over a dependent variable such as yield. This approach might result in multi-colinearity for variables, and possibly make difficulties in interpretation of the actual contribution of each variable (Hair *et al*., 1995). The solution for the problem is, therefore, complex path analysis models, which are more popular these days. A simple reason for this change could be complex models which can be a representative of biological processes in complex biological systems. The complex models are formulated as sequential models, where they reflect sequential development of crop traits and, thus, sequentiality of cause-and-effect associations among them (Kozak and Azevedo, 2014). The objective of the present study was to determine the interrelationships among yield and related characteristics in barnyard millet for developing selection criteria and for improving grain yield using an ontogeny based sequential path model.

MATERIALS AND METHODS

Plant Materials

A set of 95 germplasm accessions representing barnyard millet global variability was used in the present study. This includes 89 accessions of barnyard millet core collection developed by ICRISAT and six check genotypes (Upadhyaya *et al*., 2014). The crop was raised from July to November, 2011 and 2012 at the experimental farm, Hawalbagh of the ICAR-Vivekananda Institute of Hill Agriculture (79° 39’ E latitude and 25° 35’ N longitude, 1,250 m above msl). During 2011, a single row of each accession was planted in an augmented design, whereas two rows of each accession were planted in alpha lattice design with two replications in 2012. Five blocks constituted one replication with 19 accessions in each block. The row length was 3 m with row to row spacing of 22.5 cm. Thinning was practiced within a month of sowing to maintain plant to plant spacing of 7.5 cm within the rows.

Recommended doses of fertilizers was applied at the rate of 40:20:0 (N: P: K) kg ha^{-1}. The entire amount of phosphorous and half of the nitrogen was applied as basal dose during field preparation. The remaining half of the nitrogen was applied as top dressing after 45 days of sowing (after second weeding). Manual weeding was done twice during the crop season, 20 and 40 days after sowing to manage the weeds. No disease and insect management measures were taken as their incidence remained very low to negligible.

Data Recording

Data were recorded on 16 quantitative traits (Table 1) as per the descriptors of barnyard millet (IPGRI, 1983). For every accession in a plot, five randomly selected individual plants were used for recording the data, except for days to flowering and days to maturity, which were recorded on a plot basis. The grain yield data was also recorded on five competitive plants in each plot.

Statistical Analysis

The agro-morphological data of each year was analyzed separately using adjusted mean values. In order to predict

Table 1. Basic statistics (minimum and maximum values, arithmetic mean and Standard Deviation (SD)) for the estimated variables in Barnyard millet.

Parameter	Minimum		Maximum		Arithmetic mean		*SD*	
	2011	2012	2011	2012	2011	2012	2011	2012
DF [a]	29	31	66	67.90	49.61	50.80	10.88	8.54
DM [b]	56	58	95	91	78.90	76.07	11.27	9.75
BT [c]	1	1.14	6	9.28	2.22	2.24	1.01	1.12
CT [d]	1.91	2.5	10.45	9.2	5.63	5.38	1.74	1.18
PH [e]	71	79.68	220	156.85	149.17	125.12	31.40	17.69
NN [f]	3	4.19	11	9.16	7.41	6.76	2.16	1.15
FLL [g]	13.2	12.28	35.6	31.26	24.39	22.52	4.37	3.80
FLW [h]	1.1	1.38	3.5	3.02	2.26	2.09	0.45	0.37
FLSL [i]	6.7	6.86	17.1	14.42	9.77	9.34	2.24	1.44
PL [j]	6.1	8.09	40.2	29.84	15.30	15.18	6.94	4.44
PE [k]	0.0	-0.47	26.2	19.00	5.77	5.89	5.28	3.63
IL [l]	9.5	12.1	29.7	24.0	16.63	16.27	3.27	2.22
IW [m]	2	2.36	10	5.79	3.86	3.89	1.35	0.66
RN [n]	4	8.73	66	49.74	33.78	31.26	12.36	10.67
LRL [o]	1.3	1.78	9.5	6.16	3.48	3.19	1.54	1.06
GY [p]	2.11	4.20	42.05	24.25	11.59	12.83	7.62	4.31

[a] Days to 50% Flowering (number); [b] Days to Maturity (number); [c] Basal Tillers (number); [d] Culm Thickness (mm); [e] Plant Height (cm); [f] Number of Nodes (number); [g] Flag Leaf Length (cm); [h] Flag Leaf Width (cm); [i] Flag Leaf Sheath Length (cm); [j] Peduncle Length (cm); [k] Panicle Exsertion (cm); [l] Inflorescence Length (cm); [m] Inflorescence Width (cm); [n] Raceme Number (number); [o] Lower Raceme Length (cm), and [p] Grain Yield (g).

relationships between yield and its components, sequential path model, SPSS software (enter comment) (SPSS version 20, SPSS Inc., Chicago, IL, USA) was used. Initially, all predictor variables were entered as first-order variables over grain yield as response variable. The level of multicolinearity was measured from two common measures, namely, the "tolerance" value and the "Variance Inflation Factor" (VIF) as suggested by Hair *et al.* (1995). Tolerance value is the amount of variability of the selected independent variable not explained by other independent variables ($1-Ri^2$, where Ri^2 is the coefficient of determination for the prediction of variable i by the predictor variables). *VIF* indicates the extent of effects of other independent variables on the variance of the selected independent variable [$VIF= 1/(1-Ri^2)$]. Thus, very small tolerance value (much below 0.1) or large variance inflation factor value (above 10) indicate high colinearity (Hair *et al.*, 1995). Thereafter, ontogeny based sequential multiple regression was performed using organized first, second, third and fourth-order predictor variables to minimize colinearlity. The yield-related traits and grain yield were organized into first, second, third, and fourth-order traits (also referred to as traits at the primary, secondary, tertiary, and quaternary levels) for the ontogenetic-based sequential path analysis for each year. Each order of traits comprised several hypothetical predictor traits (causes) which were formed during certain developmental stages and one of the corresponding response traits was among the three multiplicative yield components of grain yield (Samonte *et al.*, 1998; Kozak and Azevedo 2011). The orders of the traits were assumed according to the sequences of yield component development and grain yield during the successive stages of plant ontogeny. The regression was performed separately for each response variable and its predictors. Indirect effects of predictor variables for various dependent variables were worked out using Agricolae package in R software (R Core Team, 2014).

RESULTS AND DISCUSSION

Descriptive statistics data showing the minimal and maximal values, average and standard deviation for all estimated traits of barnyard millet genotypes are presented in Table 1. The adjusted arithmetic mean of grain yield was 11.59 and 12.83 g, along with standard deviation of 7.62 and 4.31 g for the evaluation years 2011 and 2012, respectively. The minimum and maximum values for grain yield were 2.11 and 42.05 g in the year 2011, and 4.20 and 24.25 g in the year 2012.

Simple correlation coefficients computed between different pairs of characters for two evaluation seasons are presented in Table 2. A highly significant relationship was detected between most of the studied traits. Flag leaf width, culm thickness, raceme numbers, plant height, inflorescence length, number of node, days to flowering, days to maturity and flag leaf length were all significantly and positively correlated with grain yield in both the years ($P< 0.01$). However, only flag leaf width and culm thickness in 2011 and flag leaf width, raceme number and culm thickness in 2012 observed high positive correlation ($r> 0.5$). The other high positive associations ($r> 0.5$) among important traits observed during both the years were days to flowering and days to maturity *vs*. raceme number; plant height *vs*. culm thickness and number of nodes; inflorescence length *vs*. flag leaf length; flag leaf sheath length *vs*. peduncle length; peduncle length *vs*. panicle exertion and inflorescence length *vs*. raceme number. During the year 2012, grain yield showed high negative association with basal tillers and similar high negative association was also observed between number of nodes *vs*. peduncle length and panicle exertion consecutively for both years. The reasonably high estimates of associations for both years indicated that flag leaf width, culm thickness and raceme number are important grain yield component traits in barnyard millet. Gupta *et al*. (2009) and Prakash and Vanniarajan (2014) also recorded positive association of grain yield with raceme number and flag leaf width. However, positive association of finger number per ear with grain weight per ear was observed by Sonnad *et al*. (2008) in finger millet. This indicates that raceme number and flag leaf width can be good selection indices for grain yield. In addition, culm thickness and flag leaf width were found to have high positive correlation with five ear grain weight revealing the role of biomass and photosynthesis, respectively, in sink development. A very significant inference of association analysis is that in the future, while characterizing barnyard germplasm, traits *viz*., panicle exsertion, culm thickness and flag leaf sheath length which are tedious to record, could be avoided. Strong association of peduncle length and panicle exertion in finger millet was found by Upadhyaya *et al*. (2006) and he emphasized on taking observation on easy trait *viz*., peduncle length rather than panicle exertion.

Nevertheless, grain yield is a complex trait governed by low heritability and is highly affected by environmental factors. Therefore, yield components with simple genetic control that indirectly affect grain yield can be effectively used as selection criteria for improving barnyard millet grain yield. However, simple correlation analysis that relates grain yield to one or two variables may not provide a complete understanding about the importance of each component in determining grain yield (Dewey and Lu, 1959). Path coefficient analysis is a statistical technique of partitioning the correlation coefficients into its direct and indirect effects, so that the contribution of each character to yield could be estimated. Simple path analysis along with analysis of multicolinearity, where all grain yield component traits were considered as the first-order variables and grain yield as the response variable, indicated high multicolinearity for peduncle length (VIF= 60.27 in 2011 and 14.47 in 2012) and panicle exertion (VIF= 37.95 in 2011 and 11.71 in 2012) during both the years and

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Table 2. Correlation coefficients among grain yield related component traits in barnyard millet.

	GY ^{a}	DF ^{b}	DM ^{c}	BT ^{d}	CT ^{e}	PH ^{f}	NN ^{g}	FLL ^{h}	FLW ^{i}	FLSL ^{j}	PL ^{k}	PE ^{l}	IL ^{m}	IW ^{n}	RN ^{o}	LRL ^{p}
GY		0.240**	0.240**	-0.073	0.539**	0.389**	0.304**	0.228**	0.538**	0.086	-0.070	-0.096	0.316**	0.032	0.405**	0.089
DF	0.233*		0.946**	-0.171*	0.536**	0.644**	0.828**	-0.205*	-0.013	-0.344**	-0.474**	-0.429**	0.355**	-0.304**	0.583**	-0.383**
DM	0.245**	0.852**		-0.181*	0.541**	0.650**	0.859**	-0.204*	-0.055	-0.427**	-0.536**	-0.479**	0.329**	-0.367**	0.600**	-0.499**
BT	-0.615**	-0.193*	-0.243**		-0.304**	-0.147	-0.216*	-0.092	-0.341**	-0.097	0.196*	0.303**	-0.150	0.138	-0.196*	0.133
CT	0.578**	0.611**	0.542**	-0.529**		0.753**	0.620**	0.268**	0.609**	0.035	-0.168*	-0.234**	0.621**	-0.077	0.751**	-0.102
PH	0.357**	0.562**	0.552**	-0.331**	0.661**		0.731**	0.122	0.265**	0.016	-0.074	-0.072	0.684**	0.008	0.651**	-0.048
NN	0.456**	0.788**	0.796**	-0.496**	0.703**	0.655**		-0.122	0.088	-0.483**	-0.630**	-0.602**	0.385**	-0.350**	0.677**	-0.454**
FLL	0.432**	0.311**	0.461**	-0.366**	0.440**	0.536**	0.400**		0.503**	0.183*	0.112	0.077	0.559**	0.485**	0.259**	0.196*
FLW	0.765**	0.226*	0.254**	-0.589**	0.685**	0.423**	0.440**	0.618**		0.266**	0.091	-0.029	0.432**	0.195*	0.347**	0.237**
FLSL	-0.026	-0.485**	-0.565**	0.137	-0.150	-0.018	-0.536**	-0.088	-0.011		0.784**	0.615**	0.161	0.367**	-0.269**	0.638**
PL	-0.368**	-0.549**	-0.573**	0.443**	-0.437**	-0.068	-0.658**	-0.174	-0.340**	0.632**		0.957**	0.020	0.525**	-0.412**	0.697**
PE	-0.464	-0.505**	-0.482**	0.507**	-0.510**	-0.089	-0.624**	-0.192*	-0.424**	0.434**	0.925**		-0.013	0.511**	-0.415**	0.601**
IL	0.442**	0.428**	0.455**	-0.325**	0.553**	0.604**	0.454**	0.652**	0.466**	-0.069	-0.224*	-0.244**		0.364**	0.547**	0.146
IW	-0.067	0.002	0.113	0.173	-0.090	0.333**	0.007	0.340**	-0.018	0.135	0.245**	0.257**	0.316**		-0.124	0.689**
RN	0.589**	0.721**	0.689**	-0.486**	0.790**	0.672**	0.801**	0.580**	0.617**	-0.317**	-0.565**	-0.570**	0.572**	0.013		-0.326**
LRL	-0.175*	-0.289**	-0.372**	0.304**	-0.304**	-0.045	-0.400**	-0.247**	-0.290**	0.419**	0.491**	0.410**	-0.048	0.455**	-0.489**	

Correlation coefficients in 2011 and 2012 are shown in the upper and lower panels, respectively. ^{a} Grain Yield (g), ^{b} Days to 50% Flowering (number); ^{c} Days to Maturity (number); ^{d} Basal Tillers (number); ^{e} Culm Thickness (mm); ^{f} Plant Height (cm); ^{g} Number of Nodes (number); ^{h} Flag Leaf Length (cm); ^{i} Flag Leaf Width (cm); ^{j} Flag Leaf Sheath Length (cm); ^{k} Peduncle Length (cm); ^{l} Panicle Exsertion (cm); ^{m} Inflorescence Length (cm); ^{n} Inflorescence Width (cm); ^{o} Raceme Number (number); ^{p} Lower Raceme Length (cm), and * Significant at $P< 0.05$; ** Significant at $P< 0.01$ (1-Tailed test).

number of nodes (VIF= 12.34), days to flowering (VIF= 11.92) and days to maturity (VIF= 15.25) in the year 2011 (Table 3).

Sequential path analysis improves the reliability of results by placing the predictor variables in different orders of relation to the response variable and eventually eliminating the multicolinearity. Based on the ontogenic development, culm thickness, inflorescence length and raceme number were considered as first order predictors for grain yield; and the rest of the traits were fitted as second, third and fourth order predictor variables, and first order predictor variables were fitted as response variables (Figure 1). The first order predictor variables accounted for 27 and 37 per cent of the variation for grain yield in 2011 and 2012, respectively (Table 4, Figures 1-a and -b). Culm thickness showed the highest significant positive direct effect during 2011, while raceme number had the highest significant positive direct effect followed by culm thickness during the year 2012. The high direct effect of culm thickness was augmented by positive indirect effect of raceme number in 2012 resulting in high correlation of culm thickness with grain yield, whereas, the same was reduced by negative indirect effects of inflorescence length and raceme number in 2011 (Tables 4 and 5a). The results showed that high indirect effect of culm thickness for both years was responsible for significant positive correlation of inflorescence length and raceme number with grain yield. The high residual variation for both years indicated in-sufficient variables in the model for grain yield.

In the second order, the afore-mentioned first order variables (culm thickness, inflorescence length and raceme number) were considered as response variables and ontogenic sequential path analysis was performed for each of them separately (Table 4, Figures 1-a and -b). The path analysis of second order variables over first order variables showed that 67 and 74 per

Table 3. Direct effects of first-order predictor variables on grain yield and measures of colinearity in model I (all predictor variables as first-order variables over grain yield as response variable) in Barnyard millet global core collection.

Predictor variables	Direct effect		Tolerance		*VIF*	
	2011	2012	2011	2012	2011	2012
DF [a]	-0.422	-0.228	0.082	0.159	12.267	6.276
DM [b]	0.553	0.142	0.064	0.160	15.579	6.257
BT [c]	0.216*	-0.185*	0.711	0.449	1.406	2.229
CT [d]	0.122	-0.226	0.163	0.195	6.153	5.125
PH [e]	-0.007	-0.201	0.115	0.164	8.726	6.080
NN [f]	0.175	0.207	0.081	0.119	12.342	8.426
FLL [g]	0.006	-0.162	0.344	0.267	2.907	3.743
FLW [h]	0.576**	0.607**	0.335	0.270	2.983	3.701
FLSL [i]	0.694**	0.044	0.127	0.317	7.886	3.158
PL [j]	-1.876**	0.224	0.019	0.069	52.611	14.473
PE [k]	1.328**	-0.156	0.031	0.085	31.984	11.706
IL [l]	-0.252	0.160	0.246	0.409	4.061	2.447
IW [m]	-0.006	-0.145	0.291	0.423	3.431	2.365
RN [n]	0.144*	0.530**	0.279	0.143	3.590	6.978
LRL [o]	0.273*	0.278**	0.265	0.371	3.768	2.694

[a] Days to 50% Flowering (number); [b] Days to Maturity (number); [c] Basal Tillers (number); [d] Culm Thickness (mm); [e] Plant Height (cm); [f] Number of Nodes (number); [g] Flag Leaf Length (cm); [h] Flag Leaf Width (cm); [i] Flag Leaf Sheath Length (cm); [j] Peduncle Length (cm); [k] Panicle Exsertion (cm); [l] Inflorescence Length (cm); [m] Inflorescence Width (cm); [n] Raceme Number (number); [o] Lower Raceme Length (cm); * Significant at $P< 0.05$; ** Significant at $P< 0.01$ (1-Tailed test).

a. Evaluation year 2011 b. Evaluation year 2012

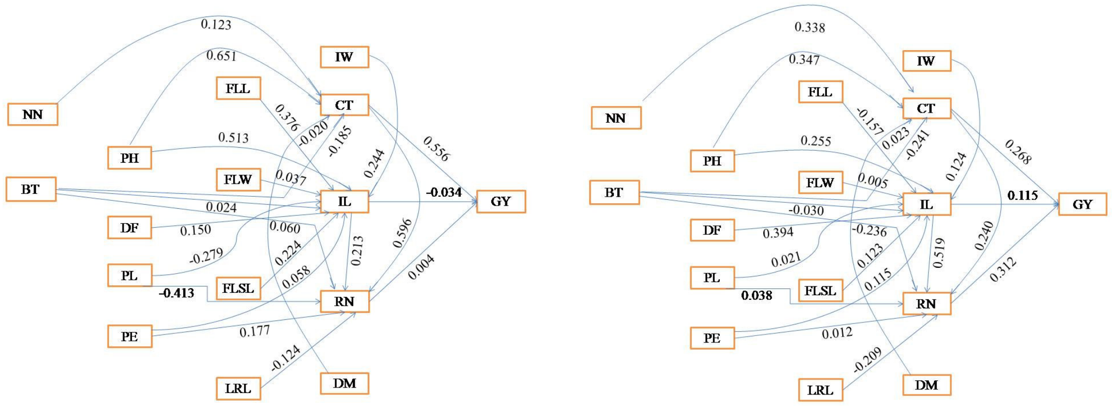

Figure 1. Ontogeny based sequential path model indicating the interrelationships among grain yield with related traits. DF: Days to 50% Flowering (number); DM: Days to Maturity (number); BT: Basal Tillers (number); CT: Culm Thickness (mm); PH: Plant Height (cm); NN: Number of Nodes (number); FLL: Flag Leaf Length (cm); FLW: Flag Leaf Width (cm); FLSL: Flag Leaf Sheath Length (cm); PL: Peduncle Length (cm); PE: Panicle Exsertion (cm); IL: Inflorescence Length (cm); IW: Inflorescence Width (cm); RN: Raceme Number (number); LRL: Lower Raceme Length (cm), and GY: Grain Yield (g).

Table 4. Sequential path model for grain yield in barnyard millet using stepwise regression analysis.

Predictor variables	Response variables	R^2 Adj	Direct effect	Predictor variables	Response variables	R^2 Adj	Direct effect
2011				2012			
CT [a]	GY	0.266	0.556**	CT	GY	0.369	0.268*
IL [b]			-0.034	IL			0.115
RN [c]			0.004	RN			0.312*
LRL [d]	RN	0.673	-0.124	LRL	RN	0.737	-0.236**
PL [e]			-0.413	PL			-0.209
PE [f]			0.177	PE			0.038
BT [g]			0.060	BT			0.012
CT			0.596**	CT			0.519**
IL [h]			0.213**	IL			0.240**
BT	IL	0.723	0.024	BT	IL	0.500	-0.030
PH [i]			0.513**	PH			0.255*
DF [j]			0.150	DF			0.124
PL			-0.279	PL			-0.157
PE			0.058	PE			0.005
FLL [k]			0.376**	FLL			0.394**
FLW [l]			0.037	FLW			0.021
FLSL [m]			0.224	FLSL			0.115
IW [n]			0.244**	IW			0.123
BT	CT	0.598	-0.185**	BT	CT	0.590	-0.241**
NN [o]			0.123	NN			0.338*
PH			0.651**	PH			0.347**
DM [u]			-0.020	DM			0.023

[a] Culm Thickness (mm); [b] Inflorescence Length (cm); [c] Raceme Number (number); [d] Lower Raceme Length (cm); [e] Peduncle Length (cm); [f] Panicle Exsertion (cm); [g] Basal Tillers (number); [h] Inflorescence Length (cm); [i] Plant Height (cm); [j] Days to 50% Flowering (number); [k] Flag Leaf Length (cm); [l] Flag Leaf Width (cm); [m] Flag Leaf Sheath Length (cm); [n] Inflorescence Width (cm); [o] Number of Nodes (number); and [p] Days to Maturity (number); * Significant at $P< 0.05$; ** Significant at $P< 0.01$ (1-Tailed test).

Table 5a. Indirect effects of first order predictor variables on grain yield of barnyard millet.[a]

Traits	CT	IL	RN	Overall effects
CT		-0.021	-0.004	0.540
		0.062	0.245	0.578
IL	0.356		-0.003	0.316
	0.150		0.177	0.442
RN	0.424	-0.018		0.405
	0.216	0.065		0.589
Residual	0.708			
	0.609			

Table 5b. Indirect effects of second order predictor variables on grain yield via Raceme Number (RN) as response variable.

Traits	LRL	PL	PE	BT	CT	IL	Overall effects
LRL		-0.297	0.308	-0.003	0.023	0.068	-0.326
		-0.120	0.031	0.000	-0.157	-0.012	-0.489
PL	0.400		0.489	-0.004	0.046	0.005	-0.412
	-0.114		0.071	0.001	-0.230	-0.052	-0.565
PE	0.354	-0.414		-0.006	0.061	-0.009	-0.415
	-0.096	-0.229		0.001	-0.266	-0.057	-0.570
BT	0.077	-0.088	0.155		0.079	-0.072	-0.196
	-0.070	-0.108	0.038		-0.277	-0.076	-0.486
CT	-0.053	0.079	-0.124	0.006		0.285	0.751
	0.070	0.108	-0.039	-0.001		0.130	0.790
IL	0.088	-0.004	-0.010	0.003	-0.159		0.547
	0.012	0.054	-0.018	-0.000	0.286		0.572
Residual	0.374						
	0.243						

Table 5c. Indirect effects of third order predictor variables on grain yield via Inflorescence Length (IL) as response variable.

Traits	BT	PH	DF	PL	PE	FLL	FLW	FLSL	IW	Overall effects
BT		-0.078	-0.032	0.062	-0.115	-0.041	0.001	-0.003	0.030	-0.150
		-0.076	-0.028	-0.069	0.011	-0.142	-0.026	0.016	0.023	-0.325
PH	-0.003		0.115	-0.028	0.027	0.053	-0.001	0.000	0.005	0.684
	0.010		0.083	0.011	-0.002	0.207	0.018	-0.002	0.045	0.604
DF	-0.003	0.339		-0.149	0.165	-0.078	0.000	-0.017	-0.064	0.355
	0.006	0.129		0.086	-0.011	0.119	0.010	-0.057	0.000	0.428
PL	0.003	-0.047	-0.085		-0.363	0.041	-0.000	0.037	0.113	0.020
	-0.013	-0.016	-0.082		0.020	-0.065	-0.015	0.074	0.034	-0.224
PE	0.005	-0.037	-0.076	0.295		0.033	0.001	0.029	0.113	-0.013
	-0.015	-0.021	-0.074	-0.145		-0.073	-0.018	0.050	0.036	-0.244
FLL	-0.002	0.068	-0.034	0.031	-0.031		-0.001	0.008	0.111	0.559
	0.011	0.124	0.046	0.027	-0.004		0.027	-0.011	0.047	0.652
FLW	-0.006	0.130	-0.005	0.031	0.012	0.205		0.013	0.043	0.432
	0.018	0.097	0.034	0.053	-0.009	0.237		-0.001	-0.003	0.466
FLSL	-0.001	0.000	-0.064	0.245	-0.233	0.070	-0.001		0.077	0.161
	-0.004	-0.005	-0.073	-0.098	0.009	-0.034	-0.000		0.019	-0.069
IW	0.002	0.010	-0.049	0.155	-0.191	0.200	-0.000	0.016		0.364
	-0.005	0.076	0.000	-0.039	0.005	0.130	-0.001	0.016		0.316
Residual	0.248									
	0.454									

[a] Indirect path effects in 2011 and 2012 are shown as the upper and lower values, respectively. DF: Days to 50% Flowering (number); DM: Days to Maturity (number); BT: Basal Tillers (number); CT: Culm Thickness (mm); PH: Plant Height (cm); NN: Number of Nodes (number); FLL: Flag Leaf Length (cm); FLW: Flag Leaf Width (cm); FLSL: Flag Leaf Sheath Length (cm); PL: Peduncle Length (cm); PE: Panicle Exsertion (cm); IL: Inflorescence Length (cm); IW: Inflorescence Width (cm); RN: Raceme Number (number); LRL: Lower Raceme Length (cm), and GY: Grain Yield (g).

Table 5d. Indirect effects of fourth order predictor variables on grain yield via Culm Thickness (CT) as response variable.

Traits	BT	NN	PH	DM	Overall effects
BT		-0.034	-0.098	0.008	-0.304
		-0.160	-0.115	-0.008	-0.529
NN	0.043		0.476	-0.038	0.620
	0.124		0.231	0.026	0.703
PH	0.027	0.108		-0.029	0.753
	0.082	0.211		0.018	0.661
DM	0.035	0.128	0.431		0.541
	0.059	0.256	0.192		0.542
Residual	0.377				
	0.397				

cent of the total variation for raceme number were explained by lowest raceme length, peduncle length, panicle exsertion, basal tiller number, culm thickness and inflorescence length in the years 2011 and 2012, respectively. Culm thickness and inflorescence length displayed high positive direct effect on raceme number in both years while, lowest raceme length showed significant negative effects during the year 2012 (Table 4). Similar trend was observed for correlation values of predictor variables with raceme number, except for culm thickness and inflorescence length whose high positive direct effects were also augmented by positive indirect effects of each other resulting in high correlation of these traits with raceme number (Table 5b). However, negative indirect effect of culm thickness decreased the correlation between raceme number and inflorescence length in the year 2011 (Table 5b).

For inflorescence length 72 and 50 per cent of the total variation was explained by the included predictor variables (Table 4) in the year 2011 and 2012, respectively. Plant height and flag leaf length during both years, and inflorescence width in the year 2011 exerted high significant positive direct effect on inflorescence length. These results were in accordance to the results of correlation analysis where both plant height and flag leaf length displayed high correlation with inflorescence length. Positive indirect effects of days to flowering and flag leaf length for plant height, and plant height and inflorescence width for flag leaf length enhanced the correlation coefficient value of plant height and flag leaf length with inflorescence length. Similarly, the direct effects of days to flowering, flag leaf width and inflorescence width were low however, the indirect effect of plant height for days to flowering, and flag leaf length for both flag leaf width and inflorescence width resulted in high correlation (Table 5c).

For culm thickness 60 and 59 per cent of the total variation was explained by basal tillers, number of nodes, plant height and days to maturity in the year 2011 and 2012, respectively. Plant height exerted significant positive effects while basal tillers displayed significant negative direct effect on culm thickness for both years. The number of nodes also showed positive significant direct effect on culm thickness in the year 2012 (Table 4). The high correlation value of number of nodes and plant height with culm thickness was mainly due to their high positive direct effect and positive indirect effect of each other on culm thickness (Tables 4 and 5d). Interestingly the very high correlation between days to maturity and culm thickness was mainly due to indirect effects via high positive effects through plant height and number of nodes while the direct effect of days to maturity was negligible on culm thickness.

Barnyard millet is an under researched crop with the least information available on major grain yield determining component traits. Few studies (Lal and Maloo, 2006; Gupta *et al*., 2009; Prakash and Vanniarajan, 2014; Prakash and Vanniarajan, 2015) were found on association and conventional path coefficient analyses in this crop. We differ from these studies in our approach of ontogeny based sequential path analysis for the development of selection indices for high grain yield. This could be the reason that our results of direct effects on grain yield differ from Prakash and Vanniarajan (2014), where they reported high direct effects of ear head length and plant height on grain yield, although both the traits were also found to be important yield determining traits in our study. We minimized the multicolinearity using step wise regression to unravel the realistic information of direct and indirect effects of different traits on grain yield, which was lacking in the previous studies. Earlier studies on sequential path analysis in wheat (Mohammadi *et al*., 2014), rice (Kozak *et al*., 2007; Li *et al*., 2014), maize (Mohammadi *et al*., 2003) and other crops (Feyzian *et al*., 2009; Dalkani *et al*., 2011; Firouzabadi *et al*., 2011; Malek *et al*., 2011) confirm the suitability of the approach followed by us in precise detection of major component traits for grain yield/economic yield. We identified the putative traits *viz*., culm thickness, raceme number, inflorescence length, plant height, flag leaf length, inflorescence width and basal tillers to be included while formulating selection index for grain yield in barnyard millet. The negative direct effect of number of basal tillers suggests optimization of number of basal tillers to achieve higher grain yield in the crop. Further, the results of ontogeny based path analyses were in agreement with correlation results for culm thickness and raceme number however, the high correlation of flag leaf width with grain yield was misleading. Although the flag leaf width was considered as a major yield determining trait through correlation analysis, it did not appear in path analyses for both the years. The lower R^2 and higher residual values indicate insufficient characters under study and there is a need to identify and include other important traits in the descriptors list of barnyard millet.

From our results, it is shown that in the indirect selection, one should pay special attention to genotypes with thick culms, more number of racemes, longer inflorescence, taller plants, longer flag leaves along with low or optimum number of tillers per plant to obtain high yield in the crop.

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صفات مرتبط به عملکرد مطلوب برای عملکرد بالای دانه با استفاده از تجزیه و تحلیل Ontogeny Based Sequential Path در ارزن Barnyard Millet (*Echinochloa spp.*).

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چکیده

رابطه بین عملکرد دانه و صفات اجزای آن می تواند راندمان برنامه های اصلاحی را توسط تعیین معیارهای منتخب و مناسب، بهبود بخشد. مطالعه بر روی کلکسیون جهانی ژرم پلاست ارزن barnyard millet (Echinochloa spp.) برای بررسی رابطه بین اجزای عملکرد و اثرات مستقیم و غیر مستقیم آن ها بر عملکرد دانه ارزن انجام شد. آزمایش ها در سال ۲۰۱۱ و ۲۰۱۲ به ترتیب در قالب طرح آگمنت و شبکه آلفا انجام شد. نتایج حاصل از ضریب همبستگی، رابطه مثبت و معنی داری در عملکرد دانه با عرض برگ پرچم و ضخامت ساقه و ارتباط منفی با پنجه های پایه و طول پدانکل در هر دو سال نشان داد. تجزیه و تحلیل های علیت، اثرات مستقیم بالای خروج خوشه، طول غلاف برگ پرچم، عرض برگ پرچم و تعداد روز تا بلوغ در سال ۲۰۱۱؛ و عرض برگ پرچم و تعداد خوشه در سال ۲۰۱۲ را نشان داد. اگرچه این میزان تخمین های مستقیم زیاد به دلیل چند خطی بودن (multicolinearity) جانبدارانه شد. بنابراین آنالیزهای ontogeny based sequential path برای ایجاد روابط علت و معلولی تعیین عملکرد دانه استفاده شد. بر اساس نتایج در طول سال، مشخص شد که ضخامت ساقه و تعداد خوشه ، صفات مهمی برای انتخاب غیر مستقیم می باشد. صفات مهم دیگر پیشنهاد شده برای گنجاندن در شاخص انتخاب، طول گل آذین، ارتفاع بوته، طول برگ پرچم، عرض گل آذین و تعداد پنجه در هر بوته بود.