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Genetic Properties of Italian Millet (*Setaria italica Beauv.*) Collected by Kagoshima University

Muneharu SATO and Teiji KOKUBU

(*Laboratoty of Plant Breeding*)

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Introduction

Italian millet (*Setaria italica* Beauv.) is no longer one of the major cerial crops in Japan. To prevent the disappearance of this genetic resource, Kagoshima University has been collecting Italian millet from all over the world since 1951. As the result of such efforts, to date over 600 strains have been maintained on its campus.

Using this millet collection, the relationship between growth period and seeding date, photoperiodic response, flowering behavior, and other fundamental characteristics of this crop were investigated[3-6]. Its improvement has not, however, been tried actively in the past, partly because the demand for this crop has not been great enough to encourage breeders to develop new cultivars and partly because genetic properties of the population have not been well described.

Today, we are enjoying extremely diversified diets our ancestors have never tasted, and yet are insatiably seeking for novel or exotic foods. This recent trend has provoked the appetite for ones once obscured. In fact, minor crops such as Italian millet have been given more credit than ever. It is important, therefore, for breeders to prepare to answer all sorts of demands society makes by developing wide varieties of new cultivars. Therefore, this study aimed to illustrate the genetic properties of the millet population collected by Kagoshima University and to evaluate its potential as a breeding source.

Materials and Methods

This study was conducted at the experimental farm in Kagoshima University, which is located in southwestern part of Kyushu, the southernmost major island of Japan. Seeds used were those collected in Japan, Korea, China, South Asian countries, India, the Soviet Union (USSR) , European countries, and African countries. In 1982, all of 615 millet strains in our collection were grown, whereas 483, 377, 546, and 252 strains were planted in 1983, 1984, 1985, and 1986, respectively.

All strains were cultivated in a single row of 90 cm long, with row-to-row and plant-to-plant spacings of 70 cm and about 5 cm, respectively. Experimental plots received 0.6 kg nitrogen (N)/a as ammonium nitrate, 1.2 kg phosphorus (P)/a as superphosphate of lime, and 1.8 kg potassium (K)/a as potassium chloride, in addition to approximately 200 kg/a of manure.

Characters observed in this study are tabulated in Table 1. All of them were recorded in 1982, but only W1000 were measured in 1983, 1984, and 1985. In 1986, PHTE, HLEN, YLD, as

Table 1. Quantitative and qualitative characters in Italian millet observed in this study

Variable name	Character or the definition of the variable
PHT4	Plant height at 4-week old
PHT5	Plant height at 5-week old
PHT6	Plant height at 6-week old
PHTF	Plant height to the flag leaf at maturity
PHTE	Plant height to the apex of the ear at maturity
CDIA	Diameter of culmn base at maturity
CCOL	Culmn base color
NOTIL	Number of tillers including the main culmn
HDAY	Number of days from planting to heading
FDAY	Number of days from planting to flowering
ELEN	Ear length
ETYPE	Ear type
BLEN	Bristle length
BCOL	Bristle color
EDIA	Ear diameter
YLD	Grain yield/ear
W1000	1000-grain weight
GLEN	Grain length with palea
GDIA	Grain daimeter with palea
ECC	Eccentricity $[(GLEN^2-GDIA^2)^{1/2}/GLEN]$ of grain
STQ	Starch quality
PCOL	Palea color
GCOL	Grain color

well as W1000 were observed.

The plant with average measurements was visually selected among normally grown healthy plants and quantitative observations for PHT4, PHT5, PHT6, PHTF, PHTE, CDIA, NOTIL, ELEN, BLEN, and EDIA were measured. For YLD and W1000, at least five plants were randomly selected among normally grown healthy plants and their averages were recorded, while GLEN and GDIA are averages of two grains and ECC was obtained by these average values. HDAY and FDAY are the numbers of days taken from planting to heading and from planting to flowering 50% of normally grown healthy plants, respectively. BLEN was interpreted as a relative value since its possible morphological function may depend on the diameter of an ear, EDIA. Specifically, it was expressed as the ratio of the actual bristle length to the radius of an ear to avoid the irrationality that unprotruding bristles of a relatively large ear should be scored higher than clearly protruding ones of a small ear.

Among qualitative characters, CCOL, ECOL, GCOL and BCOL were observed when plants were not fully matured, otherwise all of them should be orange or brown. ETYPE was classified into six types as presented in Fig. 1. Grains were crashed and dyed by iodine and potassium iodide solution to classify the starch grains into two levels of STQ: non-waxy and waxy.

All analyses were carried out by excluding missing observations and explicit outliers. The data of 1983, 1984, 1985, and 1986 were included only when heritabilities of yield related characters were estimated. Effects of variables on other variables were investigated by employing

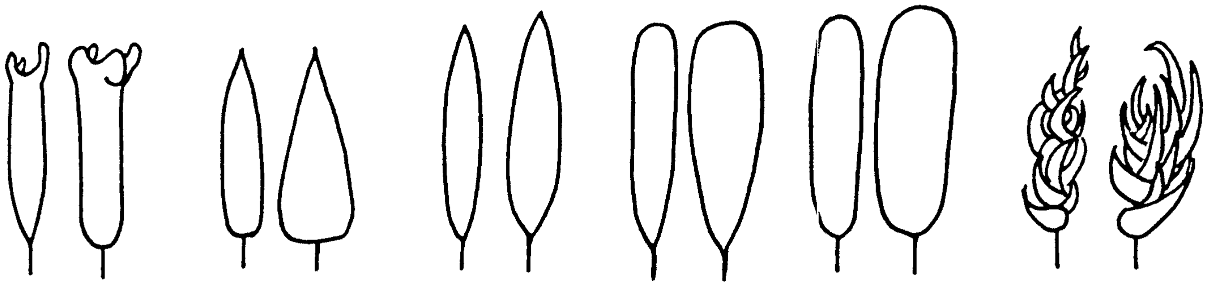

Fig. 1. Diagramatic representation of ear types classified in this study.

a series of analyses of variance, regression analyses, or chi-square analyses. Factor analyses were also employed to analyse interrelatioships among quantitative characters. After several methods were tried in the preliminary analyses, the method of principal component with a varimax rotation was eventually adopted for the final analysis. In most analyses, NOTIL was not included as a variable since majority of observations had the unique value of one.

Results and Discussion

Quantitative characters

The descriptive statistics of phenotypic measurements of economically important quantitative characters and the phenotypic correlation coefficients, including partial correlation coefficients between them are shown in Tables 2 and 3, respectively. Standard deviations, minimum values,

Table 2. Descriptive statistics on economically important quantitative characters and heritability estimates of yield related characters

Characters	Unit	Mean	Standard Deviation	Minimum Value	Maximum Value	$\hat{h}^{2}$*
PHT4	cm	21.3	5.79	7.0	47.0	
PHT5	cm	38.3	9.62	15.0	70.0	
PHT6	cm	57.8	12.86	20.0	97.0	
PHTF	cm	108.9	26.85	28.0	228.0	
PHTE	cm	139.8	29.67	46.0	250.0	17.4
CDIA	cm	0.7	0.25	0.2	1.3	
NOTIL		1.2	0.74	1.0	8.0	
HDAY	days	55.0	8.65	22.0	81.0	
FDAY	days	61.2	9.00	34.0	90.0	
ELEN	cm	17.9	4.82	4.0	37.0	8.9
BLEN		2.2	0.62	1.0	5.0	
EDIA	cm	2.7	0.89	0.7	6.0	
YLD	g	4.3	2.66	0.1	16.7	0.0
W1000	g	2.5	0.42	0.6	3.8	24.1
GLEN	mm	2.8	0.60	1.8	4.5	
GWID	mm	2.1	0.40	1.0	2.9	
ECC		0.6	0.10	0.2	0.9	

* Estimate of heritability (%) in broad sense.

Table 3. Phenotypic correlations between economically important characters in Italian millet

Characters	PHT4	PHT5	PHT6	PHTF	PHTE	CDIA	HDAY	FDAY
PHT4		0.84	0.70	0.31	0.38	0.32	−0.13	−0.08
PHT5	0.57		0.83	0.25	0.27	0.24	−0.31	−0.24
PHT6	0.11	0.52		0.18	0.20	0.11	−0.41	−0.35
PHTF	−0.10	0.06	0.05		0.89	0.45	0.52	0.54
PHTE	0.09	0.02	0.15	0.72		0.53	0.56	0.58
CDIA	0.08	0.07	−0.10	−0.01	0.08		0.30	0.30
HDAY	0.02	−0.07	−0.17	0.06	0.09	0.04		0.91
FDAY	0.04	−0.03	−0.04	−0.00	0.15	−0.01	0.78	
ELEN	0.03	−0.04	−0.09	−0.10	0.32	0.14	−0.04	−0.08
BLEN	−0.01	−0.02	0.04	−0.06	0.02	0.06	0.05	−0.11
EDIA	−0.00	0.01	0.09	−0.07	−0.02	0.34	0.01	0.00
YLD	0.09	−0.11	−0.04	−0.10	0.26	0.05	0.09	−0.06
W1000	0.03	0.06	−0.09	0.06	−0.09	−0.10	−0.11	0.10
GLEN	−0.03	0.02	−0.04	−0.04	0.03	0.08	−0.01	−0.01
GWID	0.03	−0.05	0.10	−0.04	0.03	−0.08	0.03	−0.00
ECC	−0.01	−0.06	0.08	0.05	−0.02	−0.07	−0.00	0.02

Characters	ELEN	BLEN	EDIA	YLD	W1000	GLEN	GWID	ECC
PHT4	0.28	−0.00	0.31	0.20	−0.01	−0.14	0.06	−0.36
PHT5	0.18	0.03	0.25	0.05	0.11	−0.08	0.10	−0.31
PHT6	0.09	0.06	0.18	−0.05	0.03	0.12	0.25	−0.20
PHTF	0.46	−0.11	0.44	0.51	0.08	−0.31	−0.22	−0.14
PHTE	0.58	−0.01	0.49	0.61	0.08	−0.34	−0.23	−0.19
CDIA	0.48	0.05	0.56	0.42	0.05	−0.31	−0.22	−0.18
HDAY	0.26	−0.15	0.23	0.46	−0.01	−0.29	−0.28	−0.02
FDAY	0.26	−0.18	0.24	0.44	0.03	−0.32	−0.31	−0.02
ELEN		0.04	0.46	0.50	0.24	−0.28	−0.13	−0.25
BLEN	0.06		0.14	−0.19	0.09	0.10	0.03	0.12
EDIA	0.13	0.20		0.45	0.15	−0.36	−0.25	−0.20
YLD	0.12	−0.13	0.14		0.22	−0.41	−0.28	−0.25
W1000	0.16	0.13	0.01	0.15		−0.15	0.01	−0.29
GLEN	0.02	0.04	−0.12	−0.08	−0.06		0.85	0.33
GWID	−0.01	−0.04	0.08	0.05	0.06	0.98		−0.19
ECC	−0.02	0.01	0.07	0.02	−0.03	0.94	−0.94	

The upper offdiagonal elements represent Pearson's correlation coefficients, while the lower offdiagonal elements are partial correlation coefficients controlling all other variables.

and maximum values of all characters support their wide ranges of variation, suggesting the promising potential of this population as a breeding source. Generally, other studies also reported comparable results[2,7,8], though some of the materials used by Kagawa *et al.*[2] were the duplicates of the collection of Kagoshima University and it is reasonable that they should agree with the present research.

On the growth of plant height, the slow initial growth of 0.76 cm/day was indicated, contrasting with the rapid growth from fourth week onwards, which reached 2.8 cm/day. As the rapid initial growth is desirable for overcoming the inevitable competition with weeds, the efforts in breeding to accelerate this character of Italian millet should be emphasized. Although the manipulation of one character tends to effect other characters, fortunately, as shown in Table 3, PHT4 had relatively weak associations with yield related characters.

For PHTE, the heritability in broad sense was estimated to be 17.4%. It is not large enough to show a significant genetic advance in one generation, but sufficiently great enough to make effective selections. Rao *et al.*[7] and Sandhu *et al.*[8] also estimated the heritability of plant height as 99.48% and 93.04%, respectively, their values were, however, abnormally high and were considered to be unacceptable. If they were right, efficiencies of any breeding program should be much higher.

Since the majority of strains had only one main culmn and no tiller at all, the mean of NOTIL was mear 1.2. However, some strains from Africa and India had some. Sandhu *et al.*[8] reported the average number of primary tillers/plant was 3.83 and that of secondary tillers/plant 3.15 by analysing 64 varieties collected in Afghanistan, Pakistan, Turkey, and various areas in India. These facts indicate the distinct geographical variation on this character.

Although the contribution of secondary tillers to grain yield/plant may not large, that of main tillers should be significant as the result of the experiment by Sandhu *et al.*[8] clearly showed. It is, therefore, better for breeders to develop those with several main tillers for increasing grain yield/plant.

It is known that growth period of some strains are strongly influenced by day length[3-5], therefore it is natural that the results obtained here should differ from those found in other places. But wide ranges of variation of HDAY and FDAY should be of great help for breeders to develop varieties to adapt to various places in the world.

In general, flowers bloom about one week after the heading date, and the correlation between HDAY and FDAY is high. In fall, however, the interval between heading and flowering becomes shorter.

In Table 3, both correlation coefficients of HDAY and FDAY with YLD are about 0.4 in Pearson's, whereas they are almost zero in partial correlations controlling all other variables. This explains why the result of one experiment does not necessarily agree with others, depending on characters employed in analyses[1,2,8]. Since these characters depend on day length, as discussed before, and may be influenced by many other factors, it would not be appropriate to hypothesize their direct relationships with yield related components.

Bristles of ears protruded by the length of their radii in most of the strains, therefore the mean of BLEN was 2.2 in Table 3. However, some showed no bristles outside and others extended outerward very long. Its correlations with other characters were not large enough to give any degrees of influence on them.

On the ear size, both ELEN and EDIA showed their wide ranges of variation as presented in Table 2. Since a large ear tends to have more grains/ear and also should be on the thick culmn, it is reasonable that both characters should show some associations with YLD and CDIA as in Table 3. Their partial correlations were not necessarily high, however.

Complexities in the relationships of these characters with others were indicated in the relatively large discrepancy between the values of Pearson's correlation coefficients and partial correlation coefficents, except the correlation between ELEN and PHTE.

The heritability of ELEN was estimated to be 8.9% in this study, whereas Rao *et al.*[7] obtained its exceptionally high value of 97.67% and Sandhu *et al.*[8] also came by the similarly high value of 81.11%.

Among economically important characters, grain yield may be the most important one. Fortunately, as shown in Table 2, YLD had a relatively large variation, conforming to other studies[2,7]. The maximum expected grain yield/a was about 55 kg, which happened to be as good as rice. The prospect to obtain the high yield varieties may be blight in the long run. However, if the heritability was low as found in the present experiment, the reasonable amount of genetic advance should not be expected in a few generations of selection. On this character, too, both Rao *et al.*[7] and Sandhu *et al.*[8] seemed to have overestimated its heritability. The former claimed to be 97.88%, and the latter 80.01%.

The inconsistency between the Pearson's correlation and partial correlation coefficients in Table 3 indicates the complex nature of YLD. Its intricacy would also be suggested by disagreements among the published values[1,2,8].

Another economically important character is W1000. As shown in Table 2, its variation was great enough to be used as the breeding population. Its correlation coefficients with other characters in Table 3 were small, indicating its independency to other characters. And its heritability was estimated to be an intermediate value of 24.1%. All these support the prospects that the breeding program for improving W1000 would turn out to be relatively easy. By the way, high heritability estimates, 73.27% and 73.39%, were reported by Rao *et al.*[7] and Sandhu *et al.*[8], respectively.

Both GLEN and GWID indicate the dimension of a grain. Since they are based on the measurements with palea, those presented in Table 2 should be larger than the actual grain size. Although the grain size of Italian millet is not as large as those of other cerial crops, considering its variation, it might be possible to breed it for the larger grain size.

Table 3 indicates the high correlation between GLEN and GWID. A long grain tended to be large in diameter, forming a large grain. Their Pearson's correlation coefficients with other characters were mostly negative. Among them, the negative correlation between GLEN and YLD of -0.41 would show a possible negative contribution of the grain size to grain yield, though their partial correlation coefficient was negligible.

To express the grain shape numerically, the eccentricity which shows the degree of ovalness was introduced as an indicator. In Table 1, the formula to obtain this newly introduced variable ECC was presented. Although Table 2 suggests the range of ECC as 0.7 ($=0.9-0.2$) , ECC of most of the strains fell in somewhere between 0.5 and 0.8. Table 3 showed its negative Pearson's correlations with other characters, indicating that round grains would push up other measurements. All the values, including partial correlations, were low, however.

Since it is important for breeders to estimate or predict the yield of a plant from other characters indirectly, a number of regression analyses were attempted to find some suitable models. The results were shown in Table 4. It is interesting that models with no intercept were found to be far better than those with intercept. Sandhu *et al.*[8] attempted to construct a multiple

Table 4. Some regression models to estimate grain yield

Regression models	R^2
$YLD = 0.363 \times PHT4 - 0.007 \times PHT4^2$	0.75
$YLD = 0.00022 \times PHTE^2$	0.85
$YLD^{1/2} = 0.018 \times PHTE - 0.009 \times PHT6$	(0.95)*

* This value is applied only when the dependent variable is $YLD^{1/2}$, and not YLD.

regression model of yield on five characters only to find the nonsignificant partial regression coefficints. Had they ever tried a model with no intercept, their results should have been better.

Those models in Table 4 were not necessarily ideal ones from the statistical point of view and better but complex models were also found. They are, however, simple and effective for practical uses. The first model with PHT4 as the dependent variable should be appropriate to predict the approximate yield of a plant at four weeks old.

To understand the interrelationships among quantitative characters of Italian millet, the principal component factor analysis was employed after having attempted several other methods. It was found that four factors, which might represent four independent genetic and physiological systems, would control the phenotypic expressions of these characters as shown in Fig. 2.

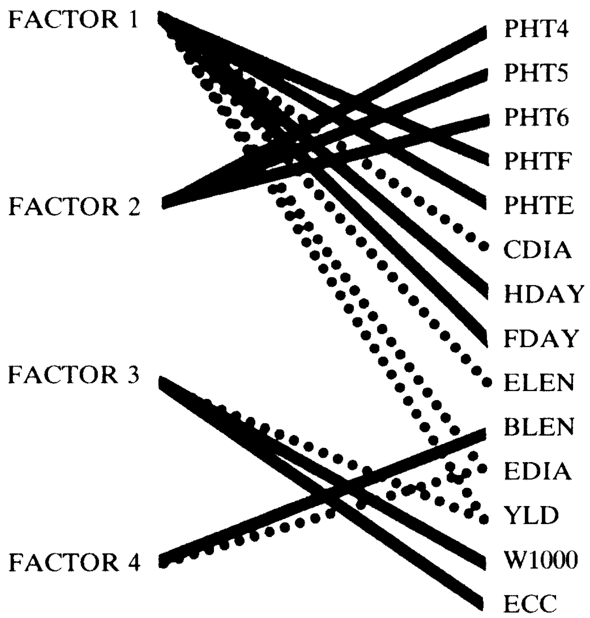

Fig. 2. The effects of factors on quantitative characters in Italian millet. The solid lines designate strong relationships, while the dotted lines indicate intermedate relationships.

YLD and EDIA seemed to be controlled by two factors, supporting their complicated relationships with other characters. Factors 1 and 4 extracted components related to growth of supportive parts of reproductive organs, whereas Factor 3 represented characters related to grain itself as grain yield, size, and shape. Factor 2 was considered to control growth of a plant.

Qualitative characters

Table 5 shows the relatioships among the major qualitative characters by denoting significance levels of dependence on other variables. It is important, however, to note the fact that the significant dependency of one character on another character does not always mean the genetic association between them, such as linkage.

STQ was found to be nonwaxy in most of the strains. Only one quarter of them showed waxiness. Since the demand for waxy grains has been increasing slightly in these days, the development of waxy varieties should be stressed.

The most common ETYPE was the Type 2 in Fig. 1. Types 1 and 6 were rare. ETYPE

Table 5. Relationships among qualitative characters

Characters	BCOL	CCOL	PCOL	GCOL	STQ
ETYPE	ns	ns	ns	ns	**
BCOL		**	**	ns	ns
CCOL			*	ns	*
PCOL				**	**
GCOL					**

**, * Significant at the 0.01 and 0.05 levels, respectively.
ns Nonsignificant at the 0.05 level.

showed no associations with other characters, but with STQ. Type 6 was found to have more waxy strains than nonwaxy ones, the total number of strains of this type was small, however. Although the statistical dependency between ETYPE and STQ was found, over all reviews of this data did not positively support any genetic links between these two characters.

On all BCOL, CCOL, PCOL, and GCOL, green counted on two thirds of all the strains, and purple followed next. Other colors were rare. Colors of these characters showed high dependency with each other, except GCOL, which showed the dependency only with PCOL. This result is reasonable since anatomically bristle, sheath of base culumn, and palea are part of leaves. However, the color dependency of different plant parts was not strict enough to imply the control of a single gene.

Statistically colors of some parts of a plant were suggested to associate with the starch quality of a grain in Table 5, though it could be caused by the data distribution rather than some kinds of genetic relationships.

Relationships between quantitative and qualitative characters

In Table 6, significance levels of effects of some qualitative characters on quantitative characters were tabulated. They does not, however, prove any genetic associations between these characters.

ETYPE seemes to influence on growth related characters, such as plant heights of various growth stages. Type 6 of ETYPE grew fastest, whereas Types 1 and 2 slowest. At maturity, Types 1 and 5 stood tallest and Types 2 and 4 lowest. Since ETYPE and EDIA are not independent to each other, it is natural that the effect of ETYPE on EDIA should be highly significant. On GLEN, Types 2 and 3 were longest, whereas Types 1 and 6 were shortest. On GDIA, Types 3 and 5 were longest, and Types 1 and 6 were also shortest.

Colors of various plant parts seemed to have some effects on some quantitative characters. BCOL influenced reproductive characters, showing favor to purple and green colors.

Both CCOL and PCOL were found to be important factors, significantly influencing many of quantitative characters. Not only green but also yellow or orange plants in these characters grew larger and yielded more than others. The distinct correspondence of quantitative characters with these colors was not, however, established in this study, since the number of strains showing colors other than green or purple in these characters was not large enough to positively prove so.

Conclusions

Both quantitative and qualitative characters of Italian millet collected by Kagoshima

Table 6. Effects of qualitative characters on quantitative characters

Characters	ETYPE	BCOL	CCOL	PCOL	GCOL	STQ
PHT4	**	ns	ns	**	ns	ns
PHT5	**	ns	ns	*	ns	ns
PHT6	**	ns	*	*	ns	ns
PHTF	**	*	**	**	ns	ns
PHTE	**	*	**	**	ns	ns
CDIA	ns	*	**	**	*	**
NOTIL	ns	ns	ns	ns	ns	**
HDAY	ns	**	**	**	ns	ns
FDAY	ns	**	**	**	*	ns
ELEN	ns	ns	**	**	ns	ns
BLEN	ns	ns	ns	ns	ns	ns
EDIA	**	*	**	**	ns	ns
YLD	ns	ns	**	**	ns	ns
W1000	ns	ns	*	**	**	**
GLEN	**	**	ns	**	ns	ns
GDIA	**	**	ns	ns	ns	ns
ECC	ns	ns	ns	**	ns	ns

**, * Significant at the 0.01 and 0.05 levels, respectively.
ns Nonsignificant at the 0.05 level.

University had wide ranges of variations, proving its promising nature as a breeding source. The independence of a character from others, as shown in low correlation coefficients between them, was also favorable for breeders to improve the specific character without influencing other characters. As heritabilities of yield related traits were found to be low, the breeding project for this crop should be based on a long range plan and it might be recommended to start with family selection, rather than individual or within-family selection to gain the maximum breeding efficiency.

Summary

The population of Italian millet (*Setaria italica* Beauv.) collected from various areas of the world by Kagoshima University was evaluated in view of propriety as a breeding source. This research was carried out at the experimental farm in Kagoshima, southwestern part of Japan from 1982 to 1986. In 1982, all of 615 strains in our collection were planted, whereas 483, 377, 546, and 252 strains were grown in 1983, 1984, 1985, and 1986, respectively. Seventeen quantitative and six qualitative characters presented in Table 1 were recorded for each strains. All analyses were conducted by excluding missing observations and explicit outliers.

As shown in Table 2, all quantitative characters displayed wide ranges of variations, implying the favorable nature of this population as a breeding source. Their heritability estimates were not, however, high enough to make rapid improvements in a few generations of selections.

Pearson's and partial correlation coefficients of quantitiative characters presented in Table 3 suggest independence of most of the characters. This characteristics of the population would make breeders easy to improve one specific character without effecting other characters. The

inconsistency of Pearson's and partial correlation coefficients of YLD with other characters suggest intricacies of this characters.

To estimate yield from other characters, some regression analyses were performed. Results in Table 4 showed practical effectiveness of these estimation models. The first one should be useful to be used in an early selection program. Incidentally, all models having intercepts failed to fit the data satisfactorily.

The result of a factor analysis presented in Fig. 2 revealed four factors controlling quantitative characters of Italian millet. YLD and EDIA seemed to be controlled by two factors. Growth of supportive parts of reproductive organs would be controled by Factor 1 and 4, whereas growth of plant itself would be regulated by Factor 2. Factor 3 would control grain yield as well as its size and shape.

Among quantitative characters, both ETYPE and GCOL did not effect most of the other quantitative characters as shown in Table 5, whereas STQ had some associations with others. It was not clear, however, whether the starch quality of grains is really genetically linked with other characters, such as ETYPE, PCOL, GCOL, *etc.* Colors of various parts of plant, especially anatomically related parts, showed interdependency among them.

Some qualitative characters seemed to effect on quantitative characters as in Table 6, though they did not prove some genetic associations between or among them. ETYPE had some influence mainly on growth related characters, whereas PCOL effected both growth and yield related characters.

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