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Morphological Differences of Italian Millet (*Setaria italica* Beauv.) among Seed Collecting Areas

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Introduction

Italian millet or foxtail millet (*Setaria italica* Beauv.), once one of the major cereal crops, is now a minor crop in most of the advanced countries. But its importance as food or feed have never been diminished from a world-wide point of view. Taking such a standpoint, Kagoshima University has been maintaining over 600 strains in its millet collection. Seed collecting areas range all over the world: China, India, Japan, Korea, the Soviet Union (USSR), African countries, European countries, and South Asian countries.

Kakubu *et al.*[4], and Kokubu and Miyazi[5,6] observed these collected materials and suggested that growth period and photoperiodic response might depend on seed collecting areas. Sakamoto[7] compared 70 strains collected in Afghanistan, Europe, Central Asia, India, Taiwan, Korea, and Japan to find characteristic differences in heading time, the number of tillers, plant height, as well as ear length.

By analysing esterase isozymes, Kawase and Sakamoto[2] investigated relationships among 432 strains of Italian millet collected at various areas throughout Eurasia. They recognized five phenotypes. They further made cross experiments among different phenotypes to carry out genetic analyses and pointed out the pecuriality of those collected in western part of Europe, which lacked the most common allele in other areas. They found some degree of phylogenetic differenciation between the Asian and European strains. They also crossed 83 strains with three testers, original places of which were Japan, Taiwan, and Belgium[3]. They studied F1 of them to analyse resemblances of these strains and induced that the first domestication of this plant was took place in an area ranging from Afghanistan to India and that it has dispersed eastward and westward.

Although geographical variations of this crop have been frame-worked through these works up to some extent, it has still been left unclarified. Therefore, in this study, it was attempted to characterize the morphological differences of Italian millet among seed collecting areas.

Materials and Methods

On July 10, 1982, seeds of 615 strains of millet in our collection were sowed at the experimental farm in Kagoshima University, which is located in the southwestern part of Kyushu, the southernmost major island of Japan. Seeds of 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 approximately 5 cm, respectively. The following fertilizers were applied: 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.

Table 1 shows characters observed in this study. The average plant 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, whereas GLEN and GDIA are averages of two grains and ECC was obtained by these average values. HDAY and FDAY are the number 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 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.

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 $[(GLEN^2\text{-}GDIA^2)^{1/2}/GLEN]$ of grain
STQ	Starch quality
PCOL	Palea color
GCOL	Grain color

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.

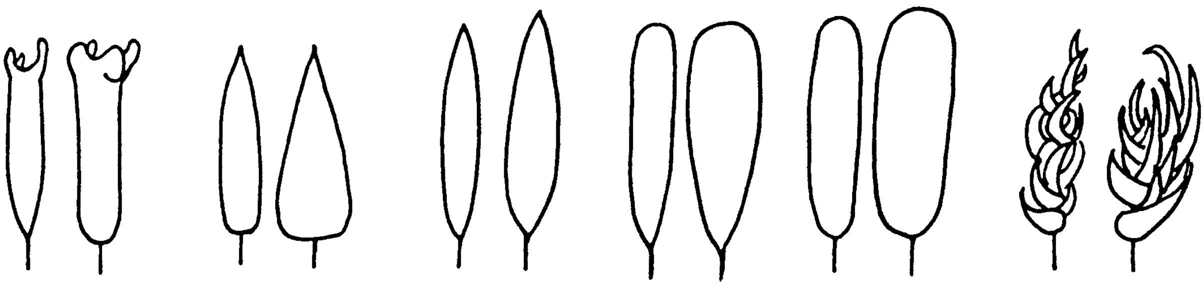

Fig. 1. Diagramatic representation of ear types classified in this study.

Significance levels of geographical diversities in characters of Italian millet were investigated by employing a series of analyses of variance, or chi-square anlyses. To classify Italian millet by seed collecting areas, several methods of cluster analyses were attempted and various numbers of clusters were extracted to be compared. In these analyses, only those areas with more than two collected strains were employed.

Results and Discussion

Means of economically important quantitative characters of Italian millet are tabulated by seed collecting areas in Table 2. And in Table 3, the results of the statistical tests on the geographical variation are presented. Significant diversities among seed collecting areas were observed virtually in all characters.

On PHT4, which represents the initial growth, those strains collected in Iwate, Austria, and China were relatively tall, whereas those collected in Sweden, Kenya, and Miyazaki stood low. Yet the number of Swedish strains was only one and it did not seem to be a really healthy plant. Therefore, this result should not be considered to represent their fundamental characteristics.

Strains collected in most of the places in Kagoshima, Miyazaki, and Philippines grew tall, presenting relatively high values of PHTF and PHTE, whereas those in Aomori, Austria, and Poland, incidentally all of them having quite few strains each, were short. Probably they did not adapt well in a warm place like Kagoshima. Generally speaking, those from relatively cool areas seemed to have performed poorly in these characters in Kagoshima. Sakamoto[7] also reported that plant height of European, Central Asiatic, and Afghan strains were very small when they were grown during the summer in Kyoto. Interesting thing is that the strains from Miyazaki grew inferiorly at first but at maturity they became tall.

Both HDAY and FDAY vary depending on the photosensitivity of plants. Kokubu and Miyazi[5,6] reported that those from the high latitudes tended to have lower sensitivity to daylight. As in the present experiment, plants were cultivated in an open field and the day length was not manipulated artificially at all, the result of this study should not be generalized.

The result showed clearly that those from the high latitudes and also from the high altitudes were apt to have shorter HDAY and FDAY. Takei and Sakamoto[9] classified 20 strains from various parts from Eurasia into three types: 1. early maturing, 2. very long basic vegetative growth period, and 3. short basic vegetative growth period and high sensitivity to day length. They claimed those of the early maturing type were mainly found in high latitude areas, agreeing with the result of the present study. Sakamoto[7] also regarded the tendency of early heading as

Table 2. Means of economically important characters in Italian millet by seed collecting areas

Seed collecting areas	Character									
	PHT4 (cm)	PHTF (cm)	PHTE (cm)	HDAY (days)	FDAY (days)	ELEN (cm)	EDIA (cm)	YLD (g)	W1000 (g)	ECC
JAPAN										
Akita	23.1	96.2	125.9	45.7	51.5	15.4	2.3	2.2	2.3	0.66
Aomori	—*	57.0	78.0	—	—	9.0	1.8	1.8	2.6	0.49
Gifu	25.0	101.0	139.0	53.0	58.0	22.0	3.0	3.8	2.5	0.61
Iwate	29.0	86.0	108.3	39.0	45.0	12.7	1.3	0.9	1.9	0.64
Kagoshima (Islands)	21.7	106.0	140.6	50.0	55.0	19.3	3.1	4.2	2.4	0.60
Kagoshima (Central)	23.3	124.0	159.3	59.8	66.4	20.7	3.4	6.7	2.7	0.60
Kagoshima (North highland)	22.4	123.4	155.3	59.1	65.5	19.6	3.1	5.8	2.5	0.61
Kagoshima (South)	20.4	124.1	158.6	62.3	69.5	19.9	3.2	6.1	2.5	0.64
Kumamoto (Highland)	21.7	99.8	129.7	48.2	54.7	17.3	2.5	4.0	2.6	0.62
Kumamoto (Central)	24.8	118.7	152.9	58.2	64.8	19.3	2.6	5.1	2.6	0.54
Miyazaki	14.8	117.0	155.0	57.3	63.0	25.5	3.3	8.0	2.2	0.63
Nagasaki (North)	22.0	95.0	118.0	53.0	59.0	17.0	5.0	3.9	2.1	0.58
Nagasaki (Hirado & Oki)	24.1	110.0	141.8	53.3	58.6	15.8	3.1	2.9	2.2	0.64
Nagasaki (South)	24.2	99.0	130.8	49.5	55.2	18.4	2.9	2.7	2.7	0.58
Nagano	21.8	86.8	114.9	45.2	51.3	16.5	2.2	3.6	2.4	0.60
Okinawa	16.4	133.0	160.1	65.4	72.2	17.7	2.3	3.7	2.3	0.68
ABROAD										
Austria	27.0	32.0	73.0	29.0	36.0	10.0	1.2	0.1	1.3	0.86
Bulgaria	22.0	52.3	79.8	36.6	40.2	11.8	1.4	1.0	3.2	0.48
China	28.7	62.4	84.0	35.1	41.0	11.4	1.4	0.6	3.3	0.62
Czechoslovakia	24.3	60.8	87.5	42.3	46.8	10.0	1.1	0.4	3.5	0.75
Finland	15.5	50.0	87.0	40.0	46.5	14.0	1.5	1.1	1.9	0.64
France	15.5	50.0	87.0	40.0	46.5	14.0	1.5	1.1	3.2	0.65
Germany	23.3	88.0	94.5	37.3	43.0	10.0	1.9	0.3	2.1	0.77
Hungary	20.8	70.5	105.0	34.0	40.5	12.0	1.6	0.3	1.8	0.73
India	18.2	105.1	129.7	53.0	58.0	15.2	2.3	2.6	2.7	0.73
Kenya	13.8	86.1	114.0	53.7	58.2	13.9	1.8	1.5	2.6	0.78
Korea	20.4	99.3	125.9	48.0	56.0	17.5	2.2	2.6	2.2	0.65
Philippines	22.4	122.8	158.3	60.4	67.4	19.0	2.0	3.9	2.0	0.68
Poland	23.0	34.0	56.0	29.0	38.0	5.0	1.2	—	—	—
Rumania	20.0	—	—	33.0	38.0	—	—	—	—	—
Sweden	12.0	44.0	61.0	39.0	44.0	11.0	1.5	0.3	2.2	0.77
Swizerland	20.0	—	—	39.0	44.0	—	—	—	—	—
Taiwan (South)	15.5	101.1	129.2	55.0	59.9	16.5	2.3	3.2	2.2	0.70
USSR (West)	21.1	51.7	77.0	44.9	60.6	10.3	1.5	0.5	2.3	0.72

* — represents a missing observation.

Table 3. Effects of seed collecting areas on characters in Italian millet

Quantitaive characters	Grand mean	Significance level	Quantitaive characters	Significance level
PHT4	21.3	**	ETYPE	**
PHT5	38.3	**	BCOL	**
PHT6	57.8	**	CCOL	ns
PHTF	108.9	**	PCOL	**
PHTE	139.8	**	GCOL	ns
CDIA	0.7	**	STQ	**
NOTIL	1.2	**		
HDAY	55.0	**		
FDAY	61.2	**		
ELEN	17.9	**		
BLEN	2.2	**		
EDIA	2.7	**		
YLD	4.3	**		
W1000	2.5	**		
GLEN	2.7	**		
GDIA	2.1	**		
ECC	0.6	**		

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

the properties of Afghan, European, and Central Asiatic strains.

The ear size was represented by ELEN and EDIA in Table 2. Most of the Japanese strains had large ears, whereas most of the foreign strains had small ones, except Korean and Philippine strains, confirming the result of the study of Sakamoto[7], which pointed out small ears of European, Central Asiatic, and Afghan strains.

Strains collected in South Kyushu performed well in YLD, contrasting with other strains. As this experiment was carried out in Kagoshima, it is possible that those with other origins might be poorly adapted, resulting in their inferior yield performance. According to Sandhu *et al.*[8], strains collected around India should perform better.

On W1000, among the Japanese strains those of Kagoshima, South Nagasaki, Kumamoto, and Aomori were heavy, whereas among the foreign origins, those of Czechoslovakia and China were heavy. Sakamoto[7] observed a wide variation in 100-grain weight in European, Central Asiatic, and Indian strains and lightness of grains in Korean and Japanese strains. It is not sure, however, whether heavy seeds of the strains collected in Aomori and Czechoslovakia might be attributable to the abundant nutriment for an individual grain as the consequence of poor seed setting, or to some genetic reasons.

The shape of grain designated by ECC characterized long grains of foreign strains, especially European, Indian, and Kenyan ones. Most of the Japanese strains were rather round, except those collected in Okinawa and Akita.

On qualitative characters, CCOL and GCOL did not show any statistically significant geographical variations, though other characters presented highly significant differences.

On ETYPE, Japanese and Korean strains displayed varieties of types. But majority of foreign strains were categorized as only Type 2 in Fig. 1. On BCOL, Japanese, Taiwanese, and Indian strains exhibited both green and purple colors, whereas other strains showed either of them. Geographical variations of PCOL were greater than BCOL. Japanese, Korean, Chinese, Taiwanese, and Indian strains presented more various colors than others.

Significant geographical deviations were found in STQ. Only Japan, Korea, Taiwan, China, India, Korea and Kenya had waxy strains. In particular, more than one quarter of Japanese and Korean strains were waxy. As the preference of starch quality may differ culturally depending on usages of grains, it may not be appropriate to correlate geographical differences with phylogenetic developement directly. It is, however, interesting that one strain collected in Kenya exhibited waxiness.

In Fig. 2, the relatioships among seed collecting areas are diagramatically shown. All quantitative characters observed in this experiment were introduced for executing various methods of cluster analyses. As a single observation may not represent the characteristics of a seed collecting area, areas with only one strain were deleted in these analyses. Only those with complete data without any missing observations on all characters were subject to analyses. The result of Ward's minimum variance method[10], which produced the most reasonable result, is presented in this figure. The rador charts in Fig. 3 were also prepared to depict the major characteristics of the hypothetical plants representing the clusters classified by this method are

Cluster 1
- Kagoshima (Central)
- Kagoshima (North highland)
- Kagoshima (South)
- Miyazaki
- Okinawa
- Philippines
- Taiwan (South)

Cluster 2
- Akita
- Kagoshima (Islands)
- Kumamoto (Highland)
- Kumamoto (Central)
- Nagasaki (Oki & Hirado)
- Nagasaki (South)
- Nagano
- Koria

Cluster 3
- Finland
- Germany
- India
- Kenya
- USSR (West)

Cluster 4
- Iwate
- China
- Hungary

Fig. 2. The cluster diagram showing the relationships among seed collecting areas on morphological characteristics.

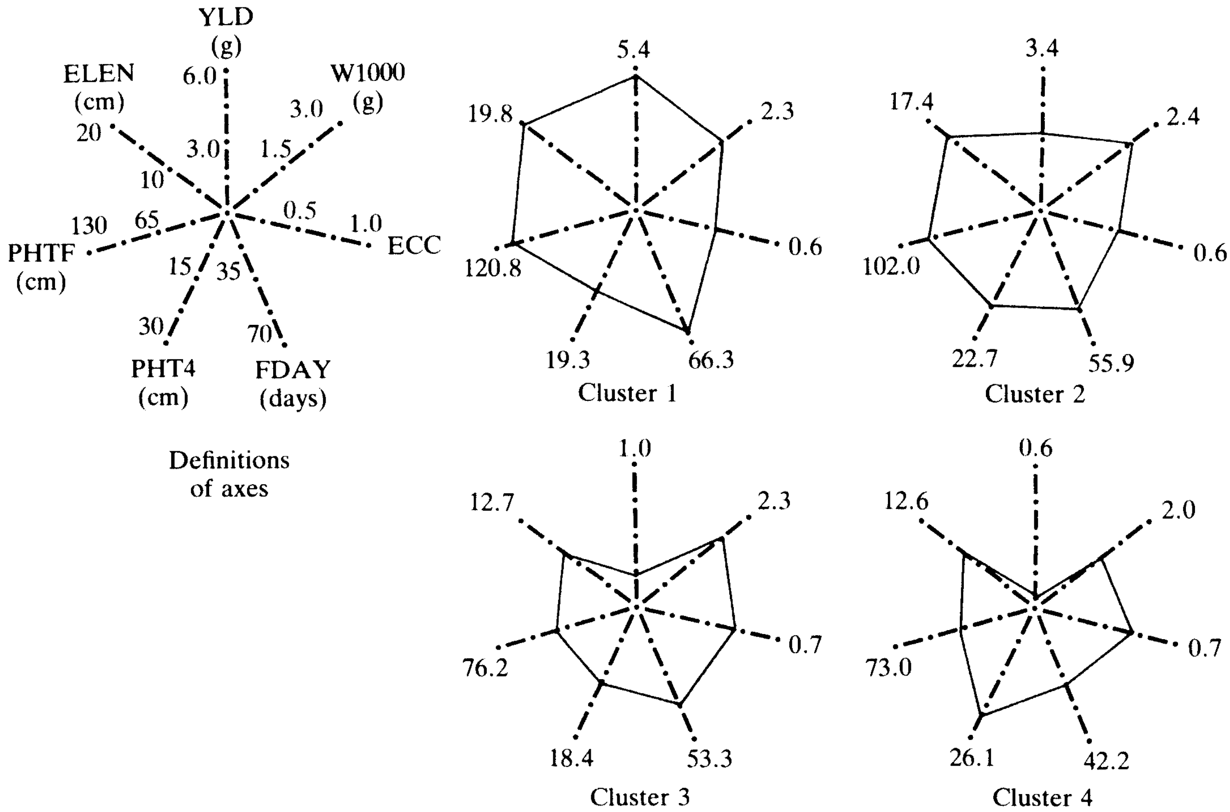

Fig. 3. Characteristics of the hypothetical plants represented by within-cluster averages of the major characters.

shown. The average of observations belonging to the same cluster was taken to express the hypothetical value of each character.

Strains collected in the mainland of Kagoshima, Miyazaki, Okinawa, Philippines, and South Taiwan were classified into one cluster, whereas those in Akita, islands of Kagoshima, Kumamoto, Nagasaki, Nagano, and Korea were grouped into another cluster. These two clusters, however, showed some degree of resemblance and could be categorized into a single cluster.

Both Clusters 1 and 2 may be characterized by relatively tall plant height, large ears, and fairly heavy round grains. Both plant height and ear length in Cluster 1 may, however, exceed those in Cluster 2. Those in Cluster 1 may typically mature slowly and yield well, contrasting with those in Cluster 2 which may grow relatively fast at first, mature intermediately, and yield intermediately.

Properties of those in Cluster 3, consisted of strains of Finland, Germany, India, Kenya, and West USSR may be slow growth, short plant height, intermediate maturity, small ears, low yield, fairly large grain size, and long grain. Fast growth, short plant height, early maturity, small ears, low yield, and small long grains may be the features of Cluster 4, formed by strains of Iwate, China, and Hungary.

By analysing F1's obtained by the crosses with testers, Kawase and Sakamoto[3] classified 83 strains of Italian millet into six types. The strains of type A were distributed in East Asia including Japan and Korea, whereas those of type B were in Taiwan and South-west islands of Japan. Those of type C were found in most of European countries. Types of AC and BC, whose

F1 produced normal pollen when crossed with testers A and B or with testers B and C, respectively, were collected in Afghanistan and India. The remaining type was found in Philippines, and Indonesia. Generally speaking, their results support the classification of the present study.

An electrophoretic study to categorize genetic variabilities of Italian millet of 10 origins, namely, China, Central Europe, France, India, Japan, Kenya, Korea, Okinawa, Taiwan, and USSR, was attempted by Jusuf and Pernes[1]. They suggested following six groups: (China-Japan-Korea), (Okinawa-Taiwan), (India-Kenya), (USSR), (Central Europe), (France). Although their conclusion did not conform perfectly with the result of the present research, a satisfactory agreement was found between these two studies, despite the distinct difference in methods. Both results proved some associations between strains collected in Okinawa and Taiwan, India and kenya, Japan and Korea, and China and some parts of Japan.

Since this study did not intend to deal with phylogenetic differentiation of Italian millet, the characterization of geographical differences in phenotypes was stressed. All results were, however, based on the data collected in the experimantal farm in one environmental condition. Therefore, it was not possible to bring out the latent abilities of some, specifically, foreign strains. To make impartial evaluations of diverse strains from various areas in the world, it would be necessary to carry out further comparative studies in multifarious environments.

Summary

To characterize geographical variations of Italian millet (*Setaria italica* Beauv.), all of 615 strains collected by Kagoshima University were grown in the experimental field in Kagoshima, the southwestern part of Japan in 1982. Quantitative and qualitative characters tabulated in Table 1 were observed for analyses.

Means of economically important quantitative characters differed significantly among seed collecting areas as shown in Tables 2 and 3. Some strains collected in the high latitudes, however, seemed to have failed to adapt the relatively warm climate of Kagoshima, resulting in poor phenotypic performances. They were also characterized by early maturity.

In general, those with slow growth rate tended to become taller and yield better, though their W1000 was not necessarily greater than others. The large plant type would be the feature of those collected in South Japan, Korea, India, Philippines, and Taiwan, whereas the small one would be the characteristic of those collected in North Japan, some European countries, and West USSR.

The grain sizes of some strains with low yield were large. This phenomenon may partly be attributable to the abundant nutriment for an individual grain due to poor seed settings. Long grains characterized European, Indian, and Kenyan strains.

On some qualitative characters, significant geographical variations were observed as shown in Table 3. In most of the characters, Japanese, and Korean strains displayed varieties of types. On STQ, waxy grains were found only in Japanese, Korean, Taiwanese, Chinese, Indian, and unexpectedly, Kenyan strains. This deviation might reflect the cultural preferences of peoples in seed collecting areas for starch quality.

Seed collecting areas were grouped into four clusters by the resemblance of morphological characters as presented in Fig. 2, and the means of some economically important characters were diagramatically represented for each cluster in Fig. 3. Cluster 1, consisted of strains collected in the mainland of Kagoshima, Miyazaki, Okinawa, Philippines, and South Taiwan, represents late

maturity, tall plants, large ears, and heavy round grains, whereas Cluster 2, consisted of those in Akita, islands of Kagoshima, Kumamoto, Nagasaki, Nagano, and Korea, features fast initial growth, intermdiate maturity, tall plants, large ears, heavy round grains, and intermediate yield. Those belonging to Cluster 3 were strains of Finland, Germany, India, Kenya, and West USSR and characterized by slow growth, intermediate maturity, small ears, low yield, and fairly large long grains. Fast growth, short plants, early maturity, small ears, low yield, and small long grains, may feature Cluster 4, formed by the strains of Iwate, China, and Hungary.

References

1) Jusuf, M. and Pernes, J.: Genetic variability of foxtail millet (*Setaria italica* P. Beauv.). Electrophretic study of five isozyme systems. *Theor. Appl. Genet.*, **71**, 385–391 (1985)
2) Kawase, M. and Sakamoto, S.: Variation, geographical distribution and genetical analysis of esterase isozymes in foxtail millet, *Setaria italica* (L.) P. Beauv. *Theor. Appl. Genet.*, **67**, 529–533 (1984)
3) Kawase, M. and Sakamoto, S.: Geographical distribution of landrace groups classified by hybrid pollen sterility in foxtail millet, *Setaria italica* (L.) P. Beauv. *Japan. J. Breed.*, **37**, 1–9 (1987)
4) Kokubu, T., Ishimine, Y., and Miyazi, Y.: Variations of growth-period of Italian millet strains, *Setaria italica* Beauv. and their response to day-length and temperature. II. Changes of growth-period of strains gathered from different districts, both native and foreign, due to the different seeding dates. *Mem. Fac. Agr. Kagoshima Univ.*, **13**, 55–75 (1977)
5) Kokubu, T. and Miyazi, Y.: Variations of growth-period of Italian millet strains, *Setaria italica* Beauv. and their resposnse to day-length and temperature. 1. Changes of growth-period of main standard varieties in Japan due to the different seeding dates. *Mem. Fac. Agr. Kagoshima Univ.*, **12**, 77–86 (1976)
6) Kokubu, T. and Miyazi, Y.: Variations of growth-period of Italian millet strains, *Setaria italica* Beauv. and their resposnse to day-length and temperature. III. Changes of growth-period due to temperature under the different day-length. *Mem. Fac. Agr. Kagoshima Univ.*, **17**, 53–68 (1981)
7) Sakamoto, S.: Origin and phylogenetic differentiation of cereals in southwest Eurasia. in Sakamoto, S. (ed.), I Cereals. in Tani, Y. and Sakamoto, S. (eds), *Domesticated plants and animals of the southwest Eurasian agro-pastoral culture complex*. p. 25–37, Kyoto Univ. The research institute for humanistic studies, Kyoto (1987)
8) Sandhu, T. S., Arora, B. S. and Singh, Y.: Interrelationships between yield and yield components in foxtail-millet. *Indian J. Agric. Sci.*, **44**, 563–566 (1974)
9) Takei, E. and Sakamoto, S.: Geographical variation of heading response to daylength in foxtail millet (*Setaria italica* P. Beauv.). *Japan. J. Breed.*, **37**, 150–158 (1987)
10) Ward, J. H.: Hierarchical grouping to optimize an objective function. *J. Am. Statist. Ass.*, **58**, 236–244 (1963)