

Agricultural complex of millets in the Indian subcontinent

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The Indian subcontinent is a wonderland for studying the domestication process of grain crops. Several species of millet are domesticated in this region. Cooking of cereals forms an important part of the agricultural complex. The agricultural complex is composed of their vernacular names, religious function, archaeological evidence, etc. The first author had participated six times in expeditions for millet research and collected numerous accessions of millets and their relative species, with information on their agricultural complex, from hundreds of farmers in their villages and fields. Ancient farmers had originally domesticated six species of millet from the relative weed species in India. Indian millet species were domesticated in the process of diffusion from humid paddy fields in Eastern India to dry upland rice fields in the Deccan Plateau, Southern India.

Key words: agricultural complex, domestication, Indian subcontinent, millet, tertiary crop

Introduction

The Indian subcontinent is a wonderland for studying the domestication process of grain crops. Several species of millet are domesticated in this region. The grain crops cultivated in this subcontinent are classified into the following four groups on the basis of geographical origin: (I) African, *Eleusine coracana* (L.) Gaertn., *Pennisetum glaucum* (L.) R. Br., and *Sorghum bicolor* Moench; (II) Mediterranean, *Hordeum vulgare* L. and *Triticum spp.*; (III) Asian, including four subgroups, (a) *Panicum miliaceum* L. and *Setaria italica* (L.) P. Beauv., (b) *Coix lacryma-jobi* L. var. *ma-yuen* (Roman.)

Stapf. and *Oryza sativa* L., (c) *Echinochloa frumentacea* (Roxb.) Link, *Panicum sumatrense* Poth., *Paspalum scrobiculatum* L., *Digitaria cruciata* (Nees) A. Camus., *Setaria pumila* (Poir.) Roem. & Schult, and *Brachiaria ramosa* (L.) Stapf.; and (d) Southwestern China, *Fagopyrum esculentum* Moench, *Fagopyrum tataricum* (L.) Gaertn.; and (IV) New World, *Zea mays* L., including *Amaranthus hypocondriacus* L., *Amaranthus caudatus* L., and *Chenopodium quinoa* Willd. These four cereal and pseudocereal groups accompanied by agricultural complexes have been introduced several times during prehistoric and historic ages from many regions into the subcontinent.

Indian food culture has been a reflection of the people's heritage. It represents India's historical development, religious beliefs, cultural practices, and above all, geographical attributes (Sahni 1986). In the Indian subcontinent, staple foods made using grain crops are served with various types of spicy curries and legume *dal* stews. Many unique cooking styles can be found for each cereal in any part of the subcontinent (Aziz 1983, Sahni 1986). Cooking of cereals forms an important part of the agricultural complex (Maeshwari 1987, Sakamoto 1988). Indian cooking consists of a unique combination of special cooking styles developed for each grain crop (Kimata et al. 2000). Moreover, the agricultural complex is composed of their vernacular names, religious function, archaeological evidence, etc.

This special issue is composed of studies on the agricultural complex, domestication process, and dispersal of millets, especially *Setaria pumila* (syn. *Setaria glauca*) and *Panicum miliaceum* and not major crops such as rice, wheat, barely, and maize, in the

Table 1. Grain crops grown in the Indian subcontinent

Geographical origin Scientific name	Japanese name	Indian name	Chromosome number	Growth habit	Botanical origin
Africa					
<i>Sorghum bicolor</i>	m orokoshi	pw ar	2n=20 (2x)	annual	<i>S. bicolor</i> var. <i>verticilliflorum</i>
<i>Pennisetum americanum</i>	to u jin-b ie	ba ja	2n=14 (2x)	annual	<i>P. violaceum</i>
<i>Eleusine coracana</i>	sh koku-b ie	ra gi	2n=36 (4x)	annual	<i>E. coracana</i> var. <i>africana</i>
Asia					
1. India					
<i>Panicum sumatrense</i>		sa m ai	2n=36 (4x)	annual	<i>P. sumatrense</i> ssp. <i>osilopodium</i>
<i>Paspalum scrobiculatum</i>		ko do	2n=40 (4x)	perenn ial	w id
<i>Echinochloa flumentacea</i>	in do-b ie	ja ngora	2n=54 (6x)	annual	<i>E. colona</i>
<i>Brachiaria ramosa</i>		ko me		annual	w id
<i>Setaria pumila</i>	ka n-enokoro	ko lati		annual	w id
<i>Digitaria cruciata</i>		ra i shan		annual	w id
2. South-eastern Asia					
<i>Coix lacryma-jobi</i> var. <i>ma-yuen</i>	ha to m u gi		2n=20 (2x)	perenn ial	<i>C. lacryma-jobi</i> var. <i>lacryma-jobi</i>
3. Central Asia					
<i>Setaria italica</i>	aw a	the nai	2n=18 (2x)	annual	<i>S. italica</i> ssp. <i>viridis</i>
<i>Panicum miliaceum</i>	ka bi	cheena	2n=36 (4x)	annual	<i>P. miliaceum</i> ssp. <i>ruderales</i>
4. South-western Asia					
<i>Fagopyrum esculentum</i>	so ba		2n=16 (2x)	annual	<i>Fagopyrum esculentum</i> ssp. <i>ancestralis</i>
<i>Fagopyrum tartaricum</i>	da tta n-so ba		2n=16 (2x)	annual	<i>Fagopyrum tartaricum</i> ssp. <i>notanini</i>
New world					
<i>Amaranthus hypocondriacus</i>	se n-n in koku		2n=32, 34 (2x)	annual	<i>A. cruentus</i> (<i>A. hybridus</i>)
<i>Amaranthus caudatus</i>	hi n o ge i to u		2n=32, 34 (2x)	annual	<i>A. cruentus</i> (<i>A. hybridus</i>)
<i>Chenopodium quinoa</i>	ka ho a		2n=36 (4x)	annual	<i>C. quinoa</i> ssp. <i>milleaunum</i>

Indian subcontinent. *Setaria pumila* has been dispersed in only a very limited area of the Deccan Plateau (Kimata 2015a, 2015b), while *Panicum miliaceum* has been dispersed throughout Eurasia (Kimata 2015d), including the Indian subcontinent, and recently North America and Australia. It is very fascinating from an environmental perspective of history and geography that the distribution patterns of *Setaria pumila* and *Panicum miliaceum* are remarkably different.

Many species of millet cultivated in the Indian subcontinent

Many species of millet are still grown by numerous farmers in the Indian subcontinent. These species are divided into three groups on the basis of place of origin: (1) Asia, including the indigenous Indian subcontinent, Central Asia, Southeast Asia, and Tibet; (2) Africa; and (3) the New World (Table 1). The following seven species of Asian millet were introduced from Central Asia, Southeast Asia, and Tibet: *Panicum miliaceum*, *Setaria italica*, *Coix lacryma-jobi* var. *ma-yuen*, *Fagopyrum esculentum*, and *Fagopyrum tartaricum*. The African millet species are *Eleusine coracana*, *Sorghum bicolor*,

and *Pennisetum glaucum*. These species were introduced via the Arabian peninsula in about 2000 BC (Sakamoto 1987, Ohnishi 1998). The New World pseudocereals are *Amaranthus caudatus*, *Amaranthus hypocondriacus*, and *Chenopodium quinoa*, and they were introduced in 19th century (Sauer 1976).

Indigenous millet species have been domesticated in the Indian subcontinent for about 3500 years (Fuller 2002). These millet species are *Echinochloa furumentacea*, *Panicum sumatrense*, *Paspalum scrobiculatum*, *Brachiaria ramosa*, *Setaria pumila*, *Digitaria cruciata*, and *Digitaria sanguinalis*. The former three species seemed to be secondary in origin through mimic and/or companion weeds with rain-fed paddy and upland rice in Eastern India. The next two species, *Brachiaria ramosa* and *Setaria pumila*, were domesticated as a secondary crop associated with the other millet species via their mimic/companion weed types in Southern India. *Digitaria cruciata* was domesticated in the late 19th century by Kashi natives in Meghalaya, and it is cultivated in the Kashi Hills (Singh and Arora 1972). Unfortunately, *Digitaria sanguinalis* has disappeared, and its origin is unclear.

Table 2. Expeditions of millet research in the Indian subcontinent between 1983 and 2001.

Year (month)	Locality	Research Team
1983.9-11	Nepal India (Haryana)	The Japanese Scientific Expedition for Nepalese Agricultural Research
1985.9-11	Pakistan (Northwest province), India (Karnataka, Andhra Pradesh, and Tamil Nadu)	Kyoto University Scientific Expedition to the Indian Subcontinent
1987.9-11	India (Jammu and Kashmir, West Bengal, Orissa, and Assam), Pakistan (India)	Kyoto University Scientific Expedition to the Indian Subcontinent
1989.9-10	Pakistan (Azad Kashmir), India (Karnataka, Madhya Pradesh, and Maharashtra)	Kyoto University Scientific Expedition to the Indian Subcontinent
1996.9~97.6	India (Karnataka, Andhra Pradesh, Tamil Nadu, Orissa, Himachal Pradesh, and Uttar Pradesh)	Research abroad supported by Japanese Government, University of Agricultural Sciences at Bangalore
2001.9-10	India (Karnataka and Orissa)	Tokyo Gakugei University Scientific Expedition to the Indian Subcontinent

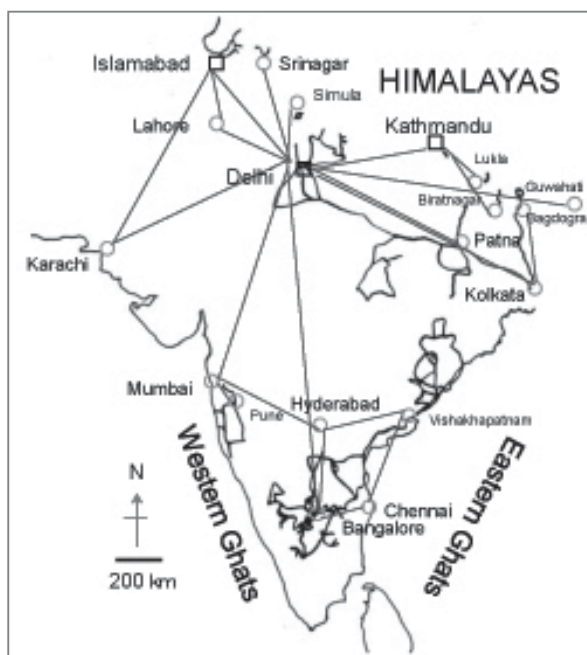


Fig. 1. Expedition routes in the Himalayas, Western Ghats and Eastern Ghats between 1983 and 2001.

A domesticated plant is always accompanied by the basic agricultural complex, which includes cultivation practices, processing, cookery, religious use, vernacular names, and other aspects.

A domestication centre for millet covers the Eastern Ghats and Southern Deccan Plateau on the basis of field observation, experimental results, linguistic sources, and archaeological data. Although this process is quite complicated among millet and its relatives, it is very effective for understanding domestication by a secondary origin via an insurance crop, a mimic companion weed, and weed types. The domestication process indicates the importance of the weed-crop complex and basic agricultural complexes as a plant-man symbiosis.

Moreover, it is obvious that several words of the old Indo-Aryan and Dravidian languages are related to the vernacular names of millets. Consequently, *Brachiaria ramosa* and *Setaria pumila* are called 'tertiary crops', which means they are double secondary crops for other millet species and upland rice. The order of first occurrence for millet species in historical sites generally supports this evolutionary process.

Field trips in the Indian subcontinent

The first author had participated six times in expeditions for millet research and collected numerous accessions of millets and their relative species, with information on their agricultural complex, from hundreds of farmers in their villages and fields (Table 2). He mainly visited the southern foot of the Himalayas and Western and Eastern Ghats in and around the Indian subcontinent between 1983 and 2001. The research team used many means of transportation, such as car, train, airplane, and their feet, for frequent field trips (Fig. 1). Particularly, the trips extended widely over Karnataka, Andhra Pradesh, Tamil Nadu, Maharashtra, Telangana, Maharashtra, Madhya Pradesh, Orissa, Chhattisgarh, Jharkhand, West Bengal, Bihar, Uttar Pradesh, Uttarakhand, Himachal Pradesh, and Jammu and Kashmir in India and the North-West Frontier in Pakistan and Eastern Nepal.

Millets domesticated in the Indian subcontinent

Ancient farmers had originally domesticated six species of millet from the relative weed species in India

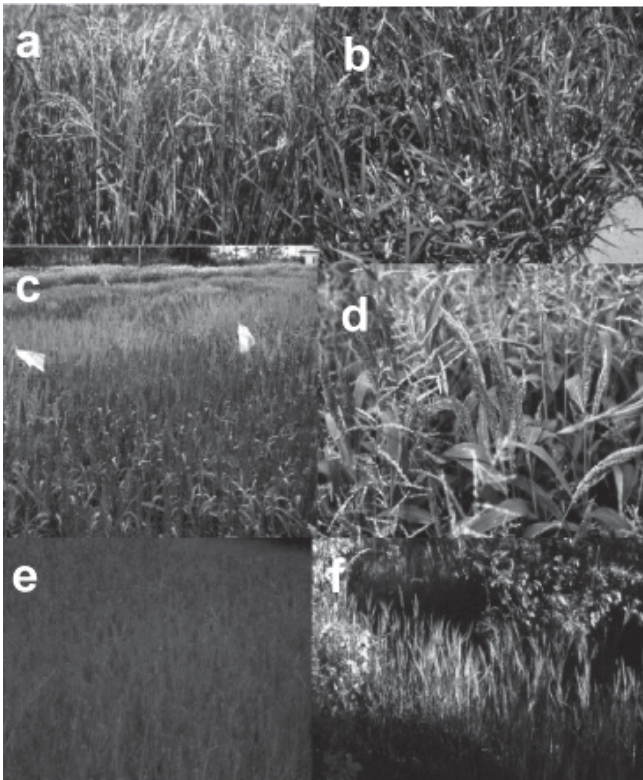


Fig. 2. Five species of millet domesticated in the Indian subcontinent and wild rice: a, *Panicum sumatrense*; b, *Paspalum scrobiculatum*; c, *Echinochloa frumentacea*; d, *Brachiaria ramosa*; e, *Setaria pumila*; and f, *Oryza rufipogon* in the irrigation canal.

(Table 1). Then, these plants were distributed over the Indian subcontinent and neighbouring areas.

Panicum sumatrense (*samai*) is an annual plant ($2n = 36$, tetraploid) derived from *Panicum sumatrense* ssp. *psilopodium* (Fig. 2a). *Paspalum scrobiculatum* (*kodo*) is a perennial plant ($2n = 40$, tetraploid, Fig. 2b). *Echinochloa frumentacea* (*jangora*) is an annual plant ($2n = 54$, hexaploid, Fig. 2c) derived from the relative weed *Echinochloa colona*. *Brachiaria ramosa* (*korne*) and *Setaria pumila* (*kolati*) are annual plants (Fig. 2d and 2e). These plants are secondary crops domesticated from their relative weeds in paddy fields. This will be discussed in detail below. *Digitaria cruciata* (*raishan*) is an annual plant derived from the relative weed grown in maize or vegetable fields (Singh and Arora 1972). In addition, *Oryza rufipogon* Griff. (wild rice) is used as an offering for gods and goddesses during festivals. It grows in ponds and irrigation canals near paddy fields (Fig. 2f).

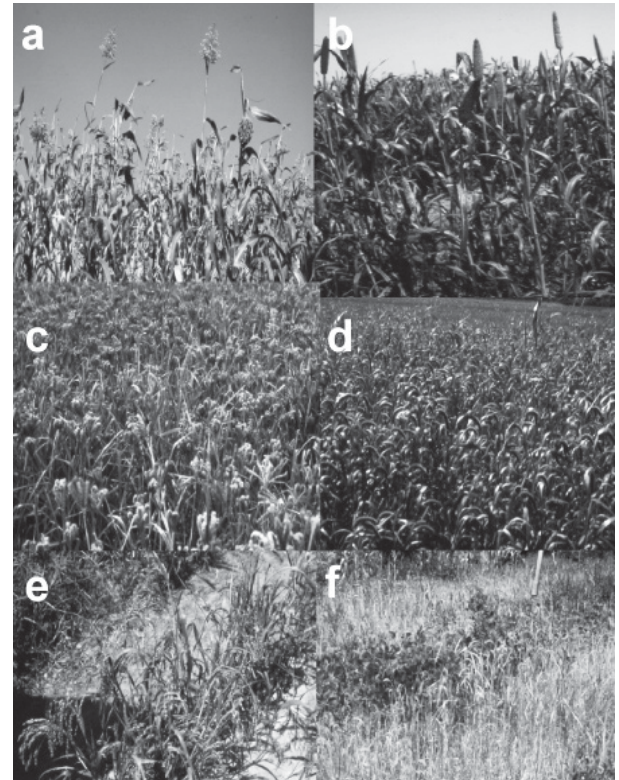


Fig. 3. Five species of millet introduced into the Indian subcontinent and a field of inter-cropping with *Setaria italica* and *Glycine max*: a, *Sorghum bicolor*; b, *Pennisetum glaucum*; c, *Eleusine coracana*; d, *Setaria italica*; e, *Panicum miliaceum*; and f, an inter-cropping field.

Other millet species grown in the Indian subcontinent

Indian farmers introduced six species of millet (Table 1) from Africa via the Arabian Peninsula, Central Asia through the Himalayas, and South-Eastern Asia via Assam in the Indian subcontinent during the Indus Civilization Age or before the dawn of history.

Sorghum bicolor (*jowar*) is an annual plant ($2n = 20$, diploid, Fig. 3a) derived from *Sorghum bicolor* var. *verticilliflorum* in Eastern Africa. *Pennisetum glaucum* (*bajra*) is an annual plant ($2n = 14$, diploid, Fig. 3b) domesticated from *Pennisetum violaceum* in Africa. *Eleusine coracana* (*ragi*) is an annual plant ($2n = 36$, tetraploid, Fig. 3c) domesticated from *Eleusine coracana* var. *africana* in Eastern Africa.

Setaria italica (*thenai*) is an annual plant ($2n = 18$, diploid, Fig. 3d) derived from *Setaria viridis*, a cosmopolitan weed in Central Asia. *Panicum miliaceum* (*cheena*) is an annual plant ($2n = 36$, tetraploid, Fig. 3e)

Table 3. Millets and their food in the Indian subcontinent

Species name	Food									
	Indian name	bhat	upma	roti	vada	dosa	idoli	mudde	ganji	mave
Japanese name	meshi		pan	age pan		mushipan	oneri	konagayu	shitogi	
<i>Sorghum bicolor</i>	○	○	◎	○	△	○	○	○	○	
<i>Pennisetum americanum</i>	○	○	◎				○	○	○	
<i>Eleusine coracana</i>	△	○	○	○	○	○	◎	○	○	
<i>Setaria italica</i>	◎	△	△	○	○		○	○		○
<i>Panicum miliaceum</i>	◎	△	○	△	△		○	○	○	
<i>Panicum sumatrense</i>	◎	○	△	○	○		○	○	○	
<i>Paspalum scrobiculatum</i>	◎		○				○	○	○	
<i>Echinochloa flumentacea</i>	◎	△			○		○	○	○	
<i>Brachiaria ramosa</i>	◎		○		○		○	○	○	
<i>Setaria pumila</i>	◎		△				△	△		
<i>Dicytaria crusiata</i>	◎		○							

◎, main ingredient used; ○, generally; △, rarely or supplement mixed.

domesticated from *Panicum miliaceum* ssp. *ruderales* in Central Asia. *Coix lacryma-jobi* var. *ma-yuen* is a perennial plant (2n = 20, diploid) domesticated from *Coix lacryma-jobi* var. *lacryma-jobi* in South-Eastern Asia. These millet species are mostly grown by mixed cropping or intercropping, for example, *Setaria italica* is grown and mixed with *Glycine max* (Leguminosae), as shown in Fig. 3f.

Moreover, five species of pseudocereals are grown in the Indian subcontinent. *Fagopyrum esculentum* and *Fagopyrum tartaricum* (both annual, 2n = 16, diploid) were introduced from Tibet. Recently, *Amaranthus caudatus*, *Amaranthus hypocondriacus* (both annual, 2n = 32 or 34, diploid), and *Chenopodium quinoa* (annual, 2n = 36, tetraploid) were dispersed from the New World.

Foods made using millets

People have cooked many types of food using millets and cereals. Mainly *bhat* (*meshi* in Japanese), *roti* (*pan*), and *mudde* (*oneri*) are cooked because they are frequently made using most of the cereals listed in Table 3 (Kimata 1987). *Bhat* is the most popular food, a boiled grain food made using all the ingredients shown in Fig. 4a, 4d right, and 5a (2nd from upper right). *Bhat* originated in ancient China and was brought to the Indian subcontinent via Eastern India. *Roti* is also a popular food made from cereal flour and originated from the cooking of wheat bread in the Fertile Crescent and was brought to the subcontinent via Western India

(Fig. 5a, 1st, 2nd, and 3rd from lower left). *Mudde* is a popular food made from cereal flour and originated from the cooking of *ugari* brought from Eastern Africa via the Arabian Peninsula (Fig. 4d and Fig. 5b). Figure 4 shows cooking methods for cereals in the Indian subcontinent: (a) a traditional boiled rice with *papad* (crispy salted wafer made from *dal*, vegetables, and cereals); (b) *upma* and *kesari bhat*; (c) *dosa*; (d) *mudde* and boiled grain made using *Brachiaria ramosa*; (e) *puli*; and (f) *idli*.

Sorghum bicolor and *Pennisetum glaucum* are mainly used for making *roti*, while *Eleusine coracana* is mostly used for making *mudde* (Fig. 5b) and fermented alcoholic drink *chan* (Fig. 6a, b, and c). Other millet species are mainly used for *bhat*. A special food, *mavu*, is made from the raw flour of *Setaria italica* and *Oryza sativa* as offering for gods and goddesses during festivals. Nine foods are made using *Brachiaria ramosa* (Fig. 5a), *mudde* is made using *Eleusine coracana* (Fig. 5b), and *chapati* is made using wheat, *Triticum aestivum* (Fig. 5c and Fig. 6d, upper). With respect to fermented foods, a starter is made from *Hordeum vulgare* (Fig. 6a, starter; 6b, a jar for fermentation; 6c, alcohol drink, *chan*, made from *Eleusine coracana*; and 6d, yogurt, *dahi*).

Other cookerries are shown in Table 3, Fig. 4, and Fig. 5. *Upma* is a coarse-ground grain food (Fig. 4b, right). *Dosa* is a thin leavened pancake stuffed with potato curry (Fig. 4c). *Idli* is a leavened pound cake made using the same ingredients as *dosa* (Fig. 4f). *Vada* is a cake made from freshly ground *dal* or millet flour. *Ganji* is a

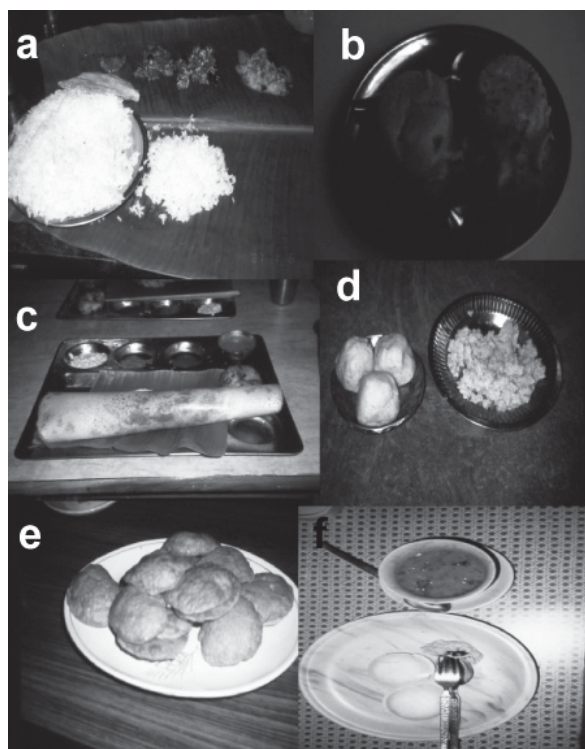


Fig. 4. Cookeries of cereal in the Indian subcontinent: a, a traditional boiled rice (*bhat*) with *papad*; b, *upuma* and *khesari bhat*; c, *dosa*; d, *mudde* and boiled grain made from *Brachiaria ramosa*; e, *puli*; f, *idoli*.

very thin starch-paste made from the same ingredients as *mudde*.

Dispersal routes of millets in the Indian subcontinent

Our team studied the domestication process and dispersal routes of Indian millets. An outline of the research results is given below.

Kodora, *Paspalum scrobiculatum*, was domesticated since about 2000 BC in India. This species is cultivated throughout the Indian subcontinent, but mainly in Madhya Pradesh. Ecological and morphological characteristics were compared using 32 accessions (including weed forms) of *Paspalum scrobiculatum*. In addition, the relationship between plant pigmentation and mimicry of rice was observed in 16 accessions, including six accessions collected from upland rice fields. Domestication process of the secondary crop to upland rice was discussed (Ishikawa unpublished). This species shifted from perennial to annual and obtained crop-like traits by accessions with rice cultivation. Both amplified fragment length polymorphism (AFLP) analysis and



Fig. 5. Cookeries of nine foods made from *Brachiaria ramosa* (a), *chapati* from wheat (b) and *mudde* from *Eleusine coracana* (c).

nucleotide sequence variation of the chloroplast *trnK/matK* region divided cultivated accessions into two groups, northern and southern groups. The northern cultivated accessions were genetically related to weed accessions collected from upland rice fields in Orissa. However, southern cultivated accessions showed close relationships to both accessions of upland rice fields in Orissa and the weed type in southern states. Furthermore, two alternate hypotheses for the origin of *Paspalum scrobiculatum* were summarized: (1) kodo millet was domesticated once in Orissa and then diffused to inland and southern states and (2) kodo millet was domesticated in Orissa and somewhere in the southern states of India, independently (Ishikawa 2007).

Jangora, *Echinochloa furumentacea*, is cultivated for food, fodder, and as an emergency crop in India, Nepal, and Pakistan. Its ancestor is a weed, *Echinochloa colona*, found in paddy fields. Morphological characteristics and AFLP analysis results of seven accessions of *Echinochloa colona* and 42 accessions of *Echinochloa furumentacea* were compared. On the basis of the results, the place of origin was assumed to be around Bihar, and then it was distributed to Tamil Nadu via Karnataka (Kagami unpublished).

Samai, *Panicum sumatrense*, is cultivated for food



Fig. 6. Fermented foods: a, starter made from *Hordeum vulgare*; b, a jar for fermentation, c, alcohol drink (*chan*) made from *Eleusine coracana* and d, yogurt, *dabi*.

and fodder in India, Nepal, Sri Lanka, and Myanmar. Its ancestor is a weed, *Panicum sumatrense* subsp. *psilopodium*, found in paddy fields. Morphological characteristics and AFLP analysis results of 38 accessions and 281 herbarium specimens of *Panicum sumatrense* were compared. On the basis of the results, the place of origin was assumed to be Eastern India, and it was then distributed in Southern India (Otsuka unpublished).

Korne, *Brachiaria ramosa*, is grown by very extensive farming for food in only India. Its ancestor is a weed found in paddy fields. Morphological characteristics and AFLP analysis results of 70 accessions of *Brachiaria ramosa*, including both weed and domesticated types, collected from Pakistan and India were compared. On the basis of the results, the place of origin was assumed to be the southern part of Orissa, and it was then distributed in the Deccan Plateau via Tamil Nadu (Otsuka unpublished).

Korati, *Setaria pumila*, is a cosmopolitan weed, but

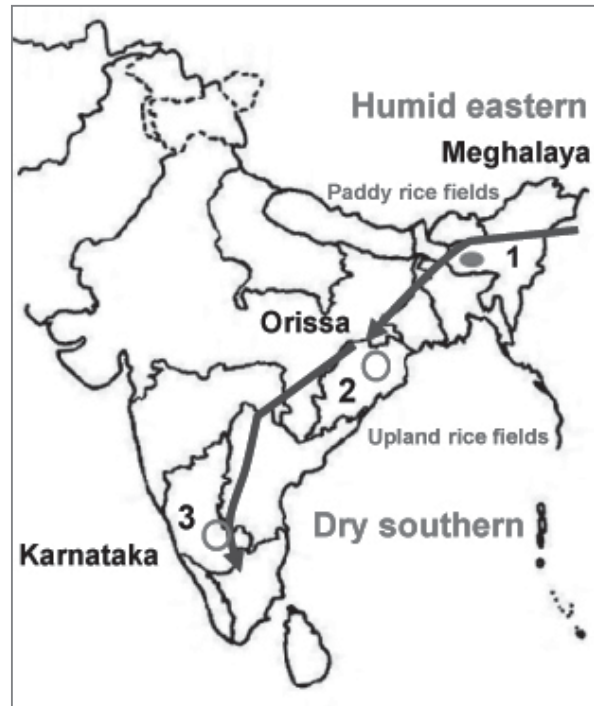


Fig. 7. Main dispersal route of Indian millets.

its domesticated type is mostly grown by mixed cropping with *Paspalum scrobiculatum* or *Panicum sumatrense* in only India (Kimata et al. 2000). This domestication process is discussed in detail below.

Dispersal route of Indian millets in the Indian subcontinent

The integrating hypothesis for the dispersal route of Indian millets is illustrated in Fig. 7 on the basis of the results. *Echinochloa furumentacea*, *Panicum sumatrense*, and *Paspalum scrobiculatum* were secondary crops to upland rice. First, their ancestral plants were companion weeds derived from the relative weeds that invaded paddy fields in humid regions of Eastern India. Second, the companion weeds became insurance crops in upland rice fields, and they spread to a dry region in the Deccan Plateau (Kobayashi 1987, 1989). *Brachiaria ramosa* and *Setaria pumila* were so called 'tertiary crops' because they were secondary crops to other millet species domesticated from their relative weeds in upland fields. On the other hand, *Digitaria cruciata* has been recently derived from the relative weed grown in maize or vegetable fields, Kashi Hill, Meghalaya, and is limited to the same area (Singh and Arora 1972).

Tentatively, Indian millet species were domesticated in the process of diffusion from humid paddy fields in Eastern India to dry upland rice fields in the Deccan Plateau, Southern India.

Acknowledgements

We had many expeditions conducted by Kyoto University, Tokyo Women's University and Tokyo Gakugei University supported by Japanese and Indian Governments in the Indian subcontinent from 1983 to 2001. The author would like to thank cordially Indian farmers for kind giving local varieties of millets; Prof. S. Sakamoto and Dr. Y. Ishikawa, Kyoto University; Dr. Y. Suyama, Tohoku University; Prof. I. Fukuda, Tokyo Women's University for their kind advice; and to the late Professor H. Kobayashi, for his excellent advice during the field survey in 1985, 1987 and 1989.

Moreover, the authors wish to express their hearty thanks to the Indian farmers in the areas of study for their valuable information and kindness; to Dr. A. Seetharam, Dr. Ashok, Dr. Madhukeshwara and Mr. Mantur, Project Coordination Cell (Small Millets), ICAR, University of Agricultural Sciences, Bangalore, India, for their collaboration and useful suggestion; to Dr. M. Nesbitt and Dr. T. Cope, Royal Botanic Gardens, Kew, UK, for their valuable suggestion on excellent collections of literatures and herbarium specimens.

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