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NOTES ON NEGLECTED AND UNDERUTILIZED CROPS

Cultivated emmer wheat (*Triticum dicoccon* Schrank), an old crop with promising future: a review

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Abstract Cultivated emmer wheat, *Triticum dicoccon* Schrank, a tetraploid species with hulled grain, has been largely cultivated during seven millennia in the Middle-East, Central and West Asia, and Europe. It has been largely replaced by hulless species and is now a minor crop, with the exception of some countries like India, Ethiopia and Yemen, where its grain is used for preparing traditional foods. Nutritional qualities and specific taste and flavor of emmer wheat products have led to a recent development of the cultivation in some European countries. Emmer wheat also possesses valuable traits of resistance to pests and diseases and tolerance to abiotic stresses and is increasingly used as a reservoir of useful genes in wheat breeding. In the present article, a review concerning taxonomy, diversity and history of cultivation of emmer wheat is reported. Grain characteristics and valuable agronomic traits are described. Some successful examples of emmer wheat utilization for the development of durum or bread wheat cultivars are examined, and the perspectives in using emmer wheat as health food and for the development of new breeding germplasm are discussed.

Keywords Breeding · Distribution · Diversity · Emmer wheat · Nutritional value · *Triticum dicoccon*

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Introduction

Emmer wheat (*Triticum dicoccon* Schrank) is one of the earliest domesticated plants and has been a staple crop over millennia (Nesbitt and Samuel 1996). It was widely cultivated in antiquity, particularly in Egypt, and until recently in a large range of countries, under different names (Table 1). It is now a minor crop, cultivated mainly in isolated, marginal areas. Its main value lies in its ability to give good yields on poor soils and resistance

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Table 1 Different vernacular names of cultivated emmer wheat, *Triticum dicoccon*

Regions	Name
Arabic Peninsula	*alas* (Yemen and Oman), *bur baladi* (Yemen)
Azerbaijan	*atchar*, *parindje*, *gotcha*
China	*er li xiao mai*
Denmark	*Emmer**, *Vinteremmer**
Ethiopia	*aja* (Amharic), *hyssa* or *matajebo* (Oromo), *arras* (Tigringa)
France	*amidonnier*, *blé de Jérusalem*
Georgia	*asli*
Germany	*Emmer**, *Emmerkorn**, *Emmerweizen**, *Zweikorn*, *Amelkorn*
Hungary	*tönke*
India	*popathiya* (Gujarat), *khapli* (Maharashtra), *ravva* (Andhra Pradesh), *godhumalu* (Tamil Nadu), *samba* (Karnataka), *jave*, *sadaka*
Italia	*farro*, *farro medio*
Netherlands	*Emmerkoorn**, *Emmertarwe**, *Tweekorn*, *Tweekoren*
Portugal	*trigo branco*
Romania	*ghireá*
Russian Federation	*dvuzernjianka*, *polba* (Russia), *piri* (Chuvashi), *vez* (Udmurtia), *boraï* (Bashkiria, Tatarstan), *khaplivadaï*; *khapli budaï* (Crimea)
Spain	*espelta bassona* (Cataluña), *escaña almidora*, *escaña mayor*, *escanda*, *escanda de dos carreras*, *escandia*, *povia*, *pavia*, *póvida*, *escanda menor* (Asturias), *ezkandia*, *ezkandia povia* (Navarra)
Ukraine	*orkich*, *luzknitza*
United Kingdom	Emmer*, Emmer wheat*, Hulled wheat, Two-grained spelt, Two-grained wheat

* The term emmer comes from the old German '*amari*'

to fungal diseases such as stem rust that are prevalent in wet areas. Some populations have also proven to be particularly tolerant to drought and heat stress. Emmer wheat consequently represents a valuable genetic resource to improve resistance to biotic and abiotic stress in bread wheat (*Triticum aestivum* L.) and durum wheat (*Triticum durum* Desf.). Information on classification and diversity of the species, its diffusion and present cultivation, and its resistance to biotic and abiotic stresses is, however, dispersed. The present review attempts to synthesize the information available on this species, including the origin, diffusion, taxonomic classification, and useful traits present in emmer wheat. This article also discusses the potential use of emmer wheat for developing new health food products. Botanical names used in the present article follow the traditional classification for wheat (Dorofeev et al. 1979).

Botanical classification

Cultivated emmer, *T. dicoccon* [syn. *T. turgidum* L. subsp. *dicoccon* (Schrank) Thell.], is a tetraploid species (BA- genomes) belonging to the genus *Triticum*, section *Dicoccoidea*, Family *Poaceae* (*Gramineae*). It was also named using numerous other synonymes such as *Gigachilon polonicum* (L.) Seidl subsp. *dicoccon* (Schrank) Á. Löve, *Spelta amylea* Ser.; *T. aestivum* L. var. *dicoccon* (Schrank) Fiori; *T. amyleum* Ser.; *T. armeniacum* (Stolet.) Nevski; *T. arras* Hochst.; *T. dicoccum* Schübler; *T. farrum* Bayle-Barelle; *T. sativum dicoccum* Hack.; *T. sativum* Lam. subsp. *dicoccum* Aschers et Graebn.; *T. spelta* Host; *T. spelta* L. var. *dicoccon* Schrank; *T. volgense* (Flaskb.) Nevski; *T. vulgare dicoccum* Alef.; *Triticum vulgare* subsp. *dicoccum* Körn.; *T. zea* Wagini. It is characterized by persistent enclosing hulls, tough glumes and a rachis that disarticulates above the spikelet at maturity (Humphries 1980). Culms are often pithy within and the leaves are frequently pubescent. Spikes are dense, laterally compressed, narrow and generally awned. The pedicel is short, narrow and pointed. Spikelets are flattened on the inner side, and usually contain two flowers. Kernels are red or white, long and slender, and acute at both ends (Leornard and Martin 1968). Glumes are often pubescent, due to the presence in most emmer accessions of the *Hg* dominant gene (Tsunewaki 1966). Emmer (like other hulled wheats) has a thinner pericarp than non-hulled wheats (Küster 1985).

Emmer wheat intraspecific classification is quite complex (Table 2). Vavilov (1964a) and Dorofeev et al. (1979) distinguished four subspecies on the basis of eco-morphological description (Fig. 1) and geographical distribution: *abyssinicum* Vav. (Abyssinian emmer), *asiaticum* Vav. (Eastern emmer), *dicoccum* (European emmer) and *maroccanum* Flaksb. (Moroccan emmer). They sub-divided the subspecies *asiaticum* into two convarieties: *serbicum* (A. Schulz) Flaksb. (Volga-Balkanian emmer) and *transcaucasicum* Flaksb. (Asian emmer) and the subspecies *dicoccum* into two convarieties as well: *dicoccum* (West European emmer) and *euscaldunense* Flaksb. (Pyrenean emmer). Vavilov (1964a) distinguished the proles *proprioabyssinicum* (Ethiopia, Eritrea), *yemenicum* (South of the Arabic peninsula) and *indostanicum* (India) within subsp. *abyssinicum*, and the proles *ibericum* (Pyrenees), *meridionale* (Southern Europe) and *bavaricum* (Western Europe) within the subsp. *dicoccum*. He also divided the convariety *transcaucasicum* of subsp. *asiaticum* into three proles: *armeno-anatolicum* (Armenia, Anatolia), *carabachicum* (Karabakh) and *iranicum* (North-Western Iran), and subsp. *maroccanum* into two proles: *montanum* Vav. (mountain regions) and *oasiculum* (lowland regions). The subspecies *abyssinicum* was also divided by Dorofeev et al. (1979) and Dedkova et al. (2007) into three ecogeographic groups or regional types (Ethiopian, Yemeni and Indian emmers).

Dorofeev et al. (1979) distinguished 8, 13, 40 and 3 botanical varieties within the subsp. *abyssinicum*, *asiaticum*, *dicoccum*, and *marocanum*, respectively. These botanical varieties have a limited agricultural significance and mainly reflect the documented existence of specific character combinations that emerged during evolution and farmer selection (Szabó and Hammer 1996). Detailed description of these botanical varieties is provided by Dorofeev et al. (1979).

Origin and domestication

Emmer wheat is one of the oldest crops in the world (Zohary and Hopf 1993; Damania 1998). It was one of the basic plants in Neolithic agriculture and its domestication was a determining factor for the beginning of agriculture (Zohary 2004). It was domesticated from the wild progenitor *Triticum dicoccoides* (Körn. ex Asch. et Graebn.) Schweinf., about 10,000 years ago (Willcox 1998). The site of domestication of the species is not completely certain. Ozkan et al. (2002) suggested the northern part of the Fertile Crescent. Investigating a larger sample of wild emmer, Mori et al. (2003) postulated that emmer wheat had been domesticated in the Kartal Dagi Mountains, North-East of Gaziantep in Turkey. Including these materials into the reassessment of their previous study, Ozkan et al. (2005) concluded that emmer was domesticated either in the Karaca Dag Mountain, West of Dyiarbakir in south-eastern Turkey, or in the Sulaimaniya region in Iran. Luo et al. (2007) showed the Sulaimaniya region to be an unlikely candidate site for emmer domestication and pinpointed emmer domestication to the Karaca Dag Mountain region. Luo et al. (2007) also postulated that the domesticated emmer genepool was enriched by gene flow from wild emmer in southern Levant (Lebanon, southwestern Syria, and Israel). The presence of domesticated emmer has been reported in many eastern Mediterranean archeological sites starting from 7400 BC (Table 3).

Diffusion of the crop

Diffusion of emmer wheat from its area of origin to Central and South-West Asia, Europe, North-East Africa, the Arabic Peninsula and the Indian subcontinent can be reconstituted thanks to the study of grain remains from archaeological excavations. At the beginning of the 7th millennium BC, domesticated emmer spread to eastern Anatolia, northern Iraq and southwestern Iran. In Iraq, remains of emmer wheat were found in mixture with einkorn and barley (*Hordeum vulgare* L.) and some intermediate forms between wild and cultivated emmer were also found (Harlan 1955). During the 6th millennium BC, emmer wheat was largely cultivated in the plains of Mesopotamia and western Anatolia. It reached Turkmenistan by the middle of the 6th millennium BC (Harris et al. 1993) when early farming villages were established in the northern foothills of the Kopet Dagh Mountains (Mellaart 1975). The earliest evidence for the presence of emmer wheat in Pakistan is from the Neolithic site of Mehrgarh (6000–5000 BC).

Table 2 Intraspecific classification and morphological description of cultivated emmer wheat by Dorofeev et al. (1979), geographic distribution of taxons, according to Dedkova et al. (2007) and resistance to rusts, powdery mildew and common bunt (Dorofeev et al. 1979, 1987)

Subsp.	Subsp. *abyssinicum* Vav. (Abyssinian emmer)	Subsp. *asiaticum* Vav. (Eastern emmer)	Subsp. *dicoccon* (European emmer)	Subsp. *maroccanum* Flaksb. (Moroccan emmer)
Convar.	–	Convar. *serbicum* (A. Schulz) Flaksb. (Asian emmer) convar. *transcaucasicum* Flaksb. (Volgo-Balkanian emmer)	Convar. *dicoccon* (West-European emmer) convar. *euscaldunense* Flaksb. (Pyrenean emmer)	–
Coleoptile bundles	2 to 6	2	2	2
Seedlings	Purple	Purple (convar. *serbicum*) green or weak purple (convar. *transcaucasicum*)	Green	Green*
Auricles	Purple	Short, often purple	Transparent, green or rarely weak purple (convar. *dicoccon*) or purple with long hairs (convar. *euscaldunense*)	Green*
Ligule	Glabrous	Glabrous or pubescent (convar. *serbicum*) pubescent (convar. *transcaucasicum*, particularly in Iranian emmers)	Weakly pubescent	Glabrous
Culm	Purple (before maturity)	Purple (before maturity), very waxy in Iranian emmers	Green	Green*
	Solid under the ear, with thin walls	Solid under the ear, with thin walls, diameter up to 2.5 mm	Diameter intermediate (2.5–4 mm, convar. *dicoccon*) or thick (up to 6 mm, convar. *euscaldunense*)	Hollow or solid
Stem	Short to intermediate (36–110 cm), resistant to lodging	Intermediate (75–120 cm), resistant to lodging (except Iranian emmers)	High (up to 150 cm)	Short (70–80 cm)
Leaf blade	Pale green, erect, rough, with rare trichomes, scabrid upper adaxial surface and glabrous abaxial surface	Semi-erect, velvety pubescent	Soft, velvety pubescent or glabrous	Glabrous
	Short (18–20 cm), 9–13 mm wide	Short (17–20 cm), 7–13 mm wide	Long (20–30 cm), 10–16 mm wide	Long (20–30 cm)
Spike	Laterally compressed, wider than thick	Strongly flattened	Strongly flattened (convar. *dicoccon*) to ovate (convar. *euscaldunense*)	Flattened, wider (8–12 mm) than thick (5–8 mm), sometimes pyramidal
	Short (5–7 cm), lax ($D = 23–30$)	Short to intermediate (5–8 cm, the longest originated from Nagorni Karabah), lax ($D = 23–27$), more rarely dense ($D = 40–50$)	Intermediate to long (7–13 cm), lax ($D = 21–30$), rarely dense	Short (5–6 cm) or intermediate (7–11 cm), semi-dense ($D = 30–40$) or dense ($D > 40$)

Table 2 continued

Subsp.	Subsp. *abyssinicum* Vav. (Abyssinian emmer)	Subsp. *asiaticum* Vav. (Eastern emmer)	Subsp. *dicoccon* (European emmer)	Subsp. *maroccanum* Flaksb. (Moroccan emmer)
Awns	Awns short to long	Awns longer than spike, rigid, and thin in convar. *serbicum*	Awns short or long, soft	1 or 2 awns, thin, long (12–17 cm)
Rachis	Hary, brittle or tough rachis	Upper part and base of the spikelets with hairy tuft (convar. *serbicum*) glabrous or laterally hairy (convar. *transcaucasicum*)	Hairy segments at the base of the spikelets (convar. *dicoccon*) or segments almost glabrous and base of the spikelets with hairy tuft (convar. *euscaldunense*)	Rachis fragile, segment laterally hairy and top and base of the spikelets with hairy tuft
Glume	Oblong-ovate, widest at the upper part	Wide and short (convar. *serbicum*) oblong-ovate, flattened, without shoulder (sometimes inverse egg-shape) or wide, inflated with elevated shoulder (convar. *transcaucasicum*)	Lanceolate or oblong-ovate (convar. *dicoccum*) or lanceolate (convar. *euscaldunense*)	Wide lanceolate, glume shorter than palea, glabrous, white or weak yellow
Keel	Weakly expressed	Weakly expressed	Strongly expressed	Strongly expressed at the base
Keel tooth	Short, blunt, weakly expressed	Short, blunt, weakly expressed (convar. *serbicum*) short and acute, or wide blunt, or oblong and weakly beak-shaped (convar. *transcaucasicum*)	Strongly expressed, acute or blunt right or beaked (convar. *dicoccum*) right, short and acute (convar. *euscaldenense*)	Short, right or weakly beak-shaped, acute or blunt
Main lateral glume vein	Toothed	Toothed weakly expressed (convar. *serbicum*) strongly or weakly expressed (convar. *transcaucasicum*)	Strongly expressed	In the middle line of the glume, finishing at the top with short tooth
Main lateral glume vein tooth	Shorter than keel tooth	Short, with a small cavity between the keel and the lateral vein tooth (convar. *serbicum*)	Near kill tooth	Shorter than keel tooth
Glume shoulder	Oblique	Absent or strongly expressed, oblique or elevated (often in convar. *transcaucasicum*)	Absent or fallen down oblique shoulder (convar. *euscaldense*)	Sometimes with broad oblique or elevated shoulder
Tillering	Low	Convar. *transcaucasicum*: low in Iranian emmer, high in Armenian-Anatolian and Nagorni Karabah emmers	High (convar. *euscaldense*)	High
Kernel	Small	Medium to big (Nagorni Karabah)	Big (in average 9 mm long)	Medium (7–8 mm long, 3–4 mm thick), red, symetric

Table 2 continued

Subsp.	Subsp. *abyssinicum* Vav. (Abyssinian emmer)	Subsp. *asiaticum* Vav. (Eastern emmer)	Subsp. *dicoccon* (European emmer)	Subsp. *maroccanum* Flaksb. (Moroccan emmer)
Growht habit	Spring	Spring	Late spring and winter (convar. *dicoccon*) principally winter, rarely semi-winter and late spring (convar. *euscaldense*)	Spring
Earliness	Very early: sowing-heading 40–45 days, sowing-maturity 75–90 days	Early or intermediate early: sowing-heading 50 days, sowing-maturity 95–100 days (convar. *transcaucasicum*) intermediate: sowing-heading 52–71 days, sowing-maturity 95–110 days (convar. *serbicum*)	Intermediate or late: sowing-heading 65–75 days, sowing-maturity 115–120 days	Early: sowing maturity 77–85 days
Distribution	Ethiopia, Eritrea, India, South Arabian peninsula	Tataria, Chuvashi,and the near regions, Yugoslavia, Bulgaria, and probably Turkey (convar. *serbicum*), and before widely distributed Middle Volga region, Crimea, Mountainous regions of Transcaucasia, Balkans, Turkey, North-West Iran, Azerbaijan, Armenia, Georgia, Dagestan, Turkey, Iran;	France, Switzerland, Germany, Austria, Italy (convar. *dicoccon*) Spain (Navara) (convar. *euscaldunense*)	Morocco: mountain region (proles *montanum*) and lowlands (proles *oasiculum*)
Resistance to diseases				
Rusts	Resistant to leaf and yellow rust (proles *proprioabyssinicum*) resistant to stem and leaf rust (proles *indostanicum*)	Resistant to leaf, stem and yellow rust (convar. *serbicum*) or susceptible to leaf and yellow rust (convar. *transcaucasicum*): proles *iranicum* and *armeno-anatolicum* more susceptible than proles *carabachicum*	Resistant to leaf and yellow rust (convar. *dicoccon*, except late forms from Bavaria that are susceptible), immune to leaf and yellow rust (convar. *euscaldense*)	Very susceptible to yellow rust, resistant (proles *montanum*) to susceptible (proles *oasiculum*)
Powdery mildew	Resistant (proles *proprioabyssinicum* and *indostanicum*) to susceptible (proles *yemenicum*)	Resistant (convar. *serbicum*) to susceptible (convar. *transcaucasicum*): proles *iranicum* and *armeno-anatolicum* more susceptible than proles *carabachicum*	Resistant (convar. *dicoccon*)	Resistant (proles *montanum*) or susceptible (proles *oasiculum*)
Common bunt	Resistant	Resistant (convar. *serbicum*) to susceptible (convar. *transcaucasicum*)	NA	NA

* Authors observations, NA-information not available

Fig. 1 Spikes (*above*) and spikelets and grains (*below*) of different subspecies (and origins) of *Triticum dicoccon*. From *left* to *right*: ssp. *abyssinicum* (Ethiopia, Yemen, India), *asiaticum* (Armenia, Iran, Serbia), *dicoccon* (Spain, Italy, Switzerland) and *marrocanum* (Morocco)

Emmer wheat was largely cultivated from the end of the 4th millennium in Georgia and from the end of the 3rd millennium in Armenia, Azerbaijan and Russia (Dorofeev et al. 1979).

In Europe, the spread of emmer wheat seems to have accompanied the development of agriculture. Emmer first diffused into Greece and Bulgaria. It reached Ukraine and Moldavia during the 6th millennium (Nesbitt and Samuel 1996), the Carpathian Mountains and the Middle Danube Basin by 5500 BC, and then diffused along the northern Mediterranean shore in southern Italy, southern France and Spain (Kipfer 2000). Agriculture did not arrive in the Swiss Alps, Germany, Poland, the British Islands or Scandinavia until 3500 BC (Ammerman and Cavalli-Sforza 1984; Barker 1985). The staple cereals of most of these early farming cultures were emmer wheat and barley. Emmer was also cultivated in North-Africa, particularly in Morocco. It is not clear if Moroccan emmer wheats derive from the spread of early farming along the Mediterranean Sea or from a later import from the nearby Iberian Peninsula. Emmer recovered from the Phoenician settlement at Volubilis, near Meknes, has been dated to the first millennium BC (University College London 2005).

In the South, emmer wheat reached Egypt during the 5th millennium BC (Nesbitt and Samuel, 1996). Archaeobotanical evidence from early farming settlements tend to demonstrate that emmer wheat was introduced into Egypt directly from the Near-East (Wetterstrom 1993). Emmer wheat was introduced into the Ethiopian highlands some 5,000 years ago through northern Sudan or southern Egypt (Helbaek 1970; Feldman 1979; Damania et al. 1992). In Yemen, emmer wheat is present in the archaeological sites of Al-Raqlah and Al-Masannah (end of the 3rd millennium) (Mehra 2003). Emmer wheats cultivated in Yemen may have been introduced from nearby Ethiopia (Nesbitt and Samuel 1996). The morphological and phenological analysis of the emmer landraces present today in Oman indicated that they belongs to the subsp. *asiaticum* and not to the subsp. *abyssinicum*, suggesting an introduction from Asia through Iran rather than from Africa through Yemen (Hammer et al. 2004; Hammer et al. 2009).

Emmer wheat was introduced into India during the 4th or 3rd millennium BC (Nesbitt and Samuel 1996). According to Kajale (1991), evidence for the presence of hulled wheats in archaeological sites in India is scarce, suggesting that emmer wheat was not very important in ancient India. Emmer wheat remains were, however, found in the Neolithic sites of Kunal in Haryana (Gosh 1989) and Kanishkapura in Kashmir (Mani 2004). They have also been found in the Harappan settlement at Rohira in Penjab (2000–1700 BC) by Saraswat (1984) and Saraswat and Pokharia (2003). Emmer wheat could have come to Kashmir from the Middle-East through Iran and Afghanistan (Mani 2004) or to southern India by sea from north-eastern Africa (Luo et al. 2007).

As shown by Fig. 2, the natural barrier of the Caucasus seems to have slowered the diffusion of emmer wheat from the region of origin to the North, compared to diffusion to the West. Similarly,

Table 3 Presence of cultivated emmer wheat in archeological sites

Site	Country	Date	Reference
Cafer Höyük XIII-X	Turkey	7400–7000 BC	Willcox (1991) and De Moulins (1993)
Tell Aswad Ib	Syria	7300–6800 BC	van Zeist and Bakker-Heeres (1984)
Aïn Ghazal	Jordan	7000–6500 BC	Rollefson et al. (1985)
Jericho PPNB	Palestine	7000–6500 BC	Hopf (1983)
Ali Kosh BM	Iran	6800–6000 BC	Helbaek (1969)
Jarmo	Iraq	6500 BC	Braidwood and Braidwood (1983)
Cap Andreas—Kastros	Cyprus	6000 BC	van Zeist (1981)
Sesklo	Greece	6000 BC	Kroll (1981)
Kovačevo	Bulgaria	6000–5700 BC	Marinova (2007)
Grotta dell'Uzzo	Italy (Sicily)	5500 BC	Costantini (1989)
Nea Nikomedia	Macedonia	5470 BC	van Zeist and Bottema (1971)
Rendina	Italy (South)	5160–4810 BC	Follieri (1982)
Jeitun	Turkmenistan	5050 BC	Charles and Hillman (1992)
Chokh	Dagestan	5000 BC	Lisitsina (1984)
Arukhlo	Georgia	5000 BC	Janushevich (1984)
	Ukraine	5000 BC	Nesbitt and Samuel (1996)
Mehrgahr	Pakistan	5000 BC	Costantini (1984)
Merimde	Egypt	4800–4400 BC	Wetterstrom (1993)
Bug Dniestr	Moldavia	4800–4700 BC	Janushevich (1984)
La Baume Fontbrégoua	France	4700–4000 BC	Courtin and Erroux (1974)
Coveta de l'Or	Spain	4670–4315 BC	Hopf and Schubart (1965)
Sammardenchia	Italy (North)	4500–4000 BC	Pessina and Rottoli (1996)
Dévaványa- Réhely	Hungary	4420 BC	Hartyáni and Nováki (1975)
Zürich lake	Switzerland	4400 BC	Jacomet et al. (1989)
Schlez	Austria	4300–3900 BC	Schneider (1994)
Hienheim	Germany	4300–3900 BC	Bakels (1978)
Aubechies	Belgium	4300–3900 BC	Bakels and Rousselle (1985)
Graetheide	Netherlands	4300–3900 BC	Bakels and Rousselle (1985)
Strachów	Poland	4300 BC	Lityńska-Zajác (1997)
Kanishkapura	India (Kashmir)	3361–2937 BC	Mani (2004)
Al-Raqlah	Yemen	~3000 BC	Mehra (2003)
Carrowmore	United Kingdom (Ireland)	3000 BC	Burenhult (1980)
Wirdmill Hill	United Kingdom (England)	2900–2500 BC	Helbaek (1952)
Balbridie	United Kingdom (Scotland)	2900 BC	Fairweather and Ralston (1993)
Kunal in Haryana	India (Haryana)	2800 BC	Gosh (1989)
Sarup	Denmark	2400 BC	Jensen (1992)
Zumbujal Torres Vedras	Portugal	2400–2200 BC	Hopf (1981)
Rogaland region	Norway	2025 BC	Bakkevig (1982)
Rohira	India (Penjab)	2000–1700 BC	Saraswat (1984)
Eker	Sweden	1500 BC	Hjelmqvist (1979)
Niuskala	Finland	1400 BC	Vuorela and Lempiäinen (1988)
Volubilis	Morocco	1000 BC	University College London (2005)

Adapted from Nesbitt and Samuel (1996) and Willcox (1998)

Indicated sites and dates correspond to the oldest, well-documented presence of emmer wheat in the corresponding countries

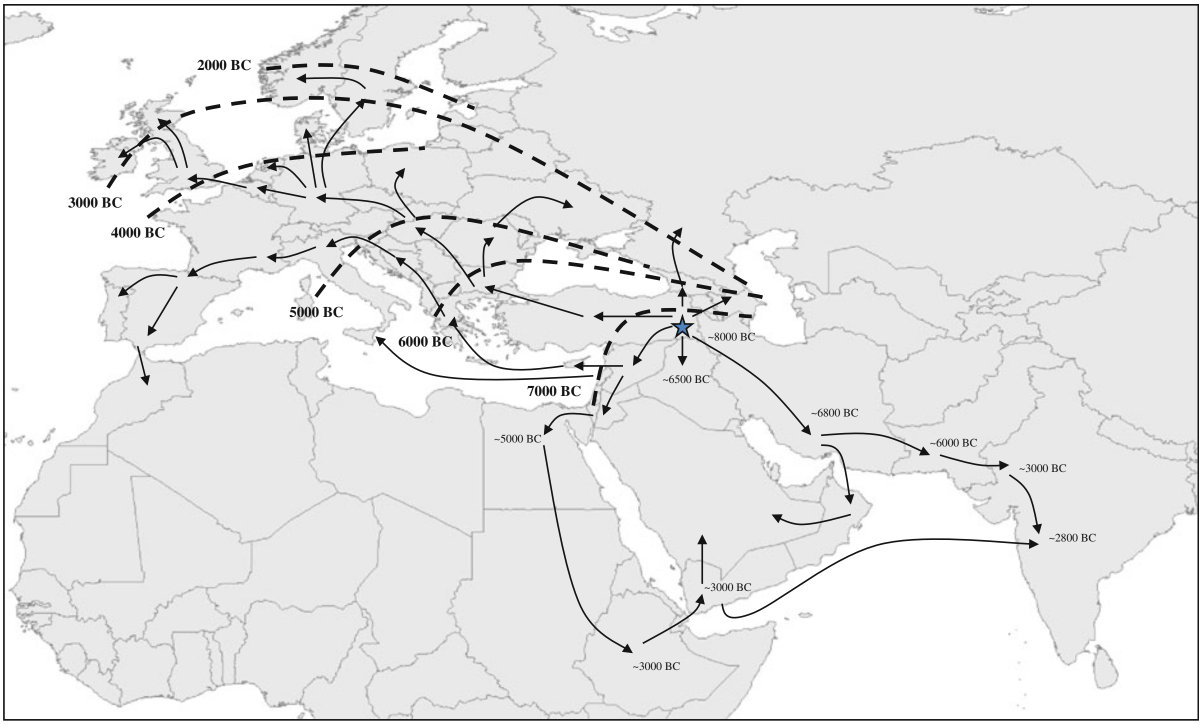

Fig. 2 Map of the diffusion of *Triticum dicoccon*, established on the basis its presence in archeological sites (see Table 3). The *star* shows the center of origin of the species and the *arrows* the presumed ways of diffusion. The *bold dotted lines* rely sites of the same date and the distance between them suggest the speed of the diffusion to the West and the North

expansion of cultivation to the South (Egypt, Ethiopia, Yemen, Oman) and East (Indian subcontinent) was probably impeded by the presence of seas (Red Sea, Indian Ocean) and mountains (Baluchistan Plateau and Hindu Ksuh and Punjab Mountains), respectively. To the West, emmer wheat diffusion was much quicker on the northern shore of the Mediterranean Sea than in the northern and continental parts of Europe and West Asia, where the species had to acclimate to harsher climates.

Apogee and decline of emmer wheat

In the Levant and southern Mesopotamia, emmer became a minor cereal in the 3rd millennium BC and disappeared by the 2nd millennium BC (Miller 1991). It has been suggested that there was a shift from emmer to barley crops due to increasing salinization of irrigated fields (Nesbitt and Samuel 1996). In eastern Turkey emmer was replaced by free-threshing wheats at the beginning of the early Bronze Age (ca 3000 BC). It is absent from the archaeobotanical records thereafter (van Zeist and Bakker-Heeres 1975; Nesbitt 1995). In central Turkey emmer appeared to be a minor crop during the Middle Bronze Age (1900–1700 BC) (Nesbitt 1993). In Turkmenistan, emmer wheat cultivation disappeared with the development of irrigation, by the Bronze Age, from 2200 BC onwards (Moore et al. 1994). Barley became the dominant crop, with free-threshing wheat second in importance. Plant remains from Troy suggests that emmer wheat was still important in western Turkey in the 2nd millennium BC (Schiemann 1951).

Emmer wheat was the main crop of Babylon, ancient Egypt and Greece (Zhukovsky 1964). In Egypt, emmer was the only wheat species cultivated from the beginnings of farming until Greco-Roman times, when it was replaced by the free-threshing durum wheat (Crawford 1979; Bowman 1990). The explanation for the extended use of emmer wheat in Egypt, long after neighbor cultures already grew free-threshing wheat, seems to correspond to a cultural choice and a definite dietary preference (Nesbitt and Samuel 1996). Herodotus (495–425 BC) mentions that the people of Egypt considered emmer 'the only fit cereal for bread' (Täckholm 1977).

During Imperial Roman times, great quantities of emmer grain were imported to Rome from Egypt (Bowman 1990). Very popular after Julius Caesar's invasion of Egypt in 47 BC and named 'Pharaoh's wheat', it was the most widespread hulled wheat in Roman Italy and sustained the Roman army (Spurr 1986). The main terms used for emmer wheat in Roman texts are *adoreum*, *ador* or *far*. In Italy emmer was still widely grown in the time of Pliny the Elder (23–79 AD) (Moritz 1958). The decline of hulled wheats in Italy was a highly regionalized process as in some regions it was still grown throughout the medieval period (Toubert 1973) and has survived until the present day (D'Antuono 1993).

In Greece, cultivation of hulled wheats continued into the Iron Age at a number of sites. Excavations of archeological sites suggest that emmer and spelt (*Triticum spelta* L.) were grown together as a mixed crop (Nesbitt and Samuel 1996). During the classical period the importance of both barley and hulled wheats sharply declined, while free-threshing wheats replaced them (Amouretti 1986; Sallares 1991).

The cultivation of emmer is attested in Spain during the ninth century by the Cronocón Albedense and during the twelfth century by the writer Ibn al-Awwam (Peña-Chocarro 1996). Emmer wheat was still an important crop in Transcaucasia up to the Iron Age (1st millennium BC) and in Ukraine and Moldavia until the Middle Ages, but its cultivation declined thereafter (Nesbitt and Samuel 1996). In the present Czech Republic, emmer wheat cultivation declined with the coming of the Slavs in the sixth century AD when it was replaced by bread wheat (Stehno 2007). It was still largely cultivated during the nineteenth century in many regions of Russia up to Siberia (Zhukovsky 1964) and in Lithuania and Belarus (Dorofeev et al. 1979).

Overall, the 1st millennium AD and more particularly the medieval period saw the replacement of hulled wheats by free-threshing wheats over most of Europe. The timing and causes for this change are unclear. As in the Near East, there is no reason to believe that the decline of emmer was only the result of the introduction of free-threshing wheats into Europe, since both tetraploid and hexaploid forms had been growing alongside hulled wheats for millennia. Jasny (1942) suggested that agricultural intensification led to an increased cultivation of the more productive free-threshing wheats.

Present cultivation

Today, emmer wheat covers only 1% of the total world wheat area and is cultivated mainly in Ethiopia, Iran, Eastern Turkey, Transcaucasia, the Volga Basin, ex-Yugoslavia, Central Europe, Italy, Spain and India (Stallknecht et al. 1996). It can still be considered as an important crop in India, Ethiopia and Yemen (Damania 1998).

In Turkey, emmer wheat was still cultivated in several regions in 1927 and represented around 2% of the cultivated area in Anatolia (Zhukovsky 1951). Ten years later, Gökgöl (1939) reported that the area sown to emmer was restricted to the Aredahan and Kars provinces (central-northern part of Turkey). In 1993, no more than 13,000 ha of hulled wheats were cultivated, with the majority of this area being planted with emmer (Karagöz 1996). In Iran, emmer wheat cultivation seems to be related to the migration of the Armenian people (Kuckuck and Schiemann 1957). The presence of emmer wheat has still been observed in 2008 in Armenian farmer's fields of the Zagros region (Hammer and Khoshbakht, personal communication). In Georgia, it was still grown in the middle of the twentieth century, in the Caucasus Mountains, at altitudes higher than 1,500 m and frequently in mixtures with oat (*Avena sativa* L.) (Zhukovsky 1964). Emmer wheat cultivation was also reported by Dorofeev et al. (1979) in the mountainous regions of Azerbaijan, Eastern Georgia, Dagestan, Armenia, Tatarstan, Udmurtia and Chuvashi. In 2006, an emmer variety 'Runo', obtained by selection within an Armenian landrace (k17560) has been released jointly by the Krasnodar Lukyanenko Research Institute of Agriculture and the Vavilov Institute of St Petersburg to be cultivated in the Northern Caucasian regions (Krasnodar Lukyanenko Research Institute of Agriculture, 2008). An emmer accession (PI94671) was collected in Afghanistan by Vavilov in 1924 (Bakhteev 1988; GRIN 2009). Hulled wheats were no longer reported in Afghanistan in the detailed surveys from Lange-de la Camp (1939), Lein (1949) and Ufer (1956).

More than 10,000 ha of emmer wheat were cultivated in Yugoslavia, often in mixtures with einkorn wheat (*Triticum monococcum* L.), until 1956 (Borojević 1956; Pavićević 1973). Small populations were reported in Bosnia Herzegovina, Croatia, Montenegro and Serbia up to the mid 1970′s (Pavićević 1990). In 1991, emmer wheat accessions were reported in the Dinara Mountain region, mixed with oats, and in the village of Sovići, Bosnia-Herzegovina, mixed with einkorn (Ohta and Furuta 1993). In Italy, emmer wheat was cultivated for many centuries in several regions of central Italy (Apennines Mountains) and in Sicily, under the name of *farro medio*. Both autumn-sown winter and spring-sown spring types were grown in Italy. Winter types were cultivated all along the Apennines mountain chain, between 40° and 44° N in latitude, while spring types were grown in a restricted area of the central Apennines (D'Antuono and Pavoni 1993). The spring type was also cultivated as an emergency crop, when cultivation of winter wheat had failed. About 30 years ago, it was thought that emmer wheat was no longer grown in the country (Pantanelli 1944; Ciferri and Bonvicini 1959; Laghetti et al. 2009). However, Perrino et al. (1981) reported the presence of emmer wheat in South Italia. The cultivation of emmer wheat in this region was further more comprehensively described and discussed by Perrino and Hammer (1982, 1983), Perrino et al. (1982, 1984) and Hammer and Perrino (1984). This re-discovering of the *farro medio* has led to a revival of the interest for this crop in Italy (D'Antuono 1995) and throughout Europe (Padulosi et al. 1996). The area sown to emmer wheat in Italy has grown to around 2,000 ha in recent years (Pagnotta 2003).

In the other European countries, emmer wheat was cultivated until the middle of the twentieth century, mainly in mountainous areas. In France, the most cultivated landrace were the 'amidonnier blanc' (also called 'épeautre de Mars', 'épautre du Cap d'hiver', or 'amidonnier de Tartarie') and the 'amidonnier roux' (or 'amidonnier de Tarascon') (Denaiffe et al. 1928). In Spain, the presence of emmer wheat during the nineteenth century was reported by Willkomm (1852) and by the botanists Clemente and Lagasca (Téllez Molina and Alonso Peña 1952). Emmer wheat landraces with red and black spikes were cultivated in Old Castilla and Baleares Islands, respectively (Werner, 1895). Emmer cultivation was still important during the first part of the twentieth century but dropped during the Spanish Civil War (Peña-Chocarro 1996). In the 1950s cultivation was already limited to Navarra, Huesca and Asturias. The main landraces were 'escaña doble de cañada del hoyo' in Cuenca, 'ezcandia' in Navarra, 'escaña de graus' in Huesca, and 'povia blanca de Somiedo', 'povia blanca', 'escandia povia de Malvedo', 'escanda de la abundancia' and 'povia roja' in Asturias (Gadea 1954). Emmer wheat almost disappeared from Navarra in 1971 (Peña-Chocarro and Zapata 1997), but is still cultivated in Asturias, mainly in mixtures with spelt wheat (Peña-Chocarro 1996). In Morocco, there was evidence of emmer cultivation during the first part of the twentieth century (Miége 1924, 1925) but information is lacking concerning its present cultivation. Emmer wheat is also punctually cultivated in Central Europe, particularly in the white Carpathian Mountains (Kühn 1970; Hanelt and Hammer 1975). Interestingly, the landraces cultivated in this region do not belong to the European form, but to the *asiaticum* form, convariety *serbicum* (Kühn et al. 1976). Some recent developments of the cultivation are described in the Czech Republic by Konvalina and Moudrý (2007) and in Slovakia by Bareš et al. (2008). In Sweden, emmer was observed until the 1960s, in mixtures with spelt wheat interspersed with bread wheat fields (Hjelmqvist 1966).

In Egypt, emmer cultivation progressively disappeared. It was mentioned by Werner (1895) in the nineteenth century, but only free-threshing wheats are grown today (Zahran and Willis 1992). In Ethiopia, considered as the secondary center of diversity for tetraploid wheats, a remarkable diversity of emmer wheats was collected by Vavilov in 1927 (Vavilov 1951). Today, emmer represents about 7% of Ethiopia's entire wheat production (BOSTID 1996). It is primarily produced for house hold consumption and occasionally for regional market (D'Andrea and Haile 2002). Emmer wheat is cultivated in marginal lands in almost all regions of the country (Gonder, Gojam, Welo, Tigray, Shewa, Bale, Arsi, Hararge, Sidamo and Gamu Gofa), in altitudinal ranges of 1,800–3,000 m (Institute of Biodiversity Conservation of Ethiopia, unpublished). It is one of the major cereal crops in the Bale zone of south eastern Ethiopia (Demissie and Hailegiorgis 1985) and is consciously grown in mixtures with other tetraploid wheats and bread wheat by farmers from Bale and Welo (Eticha et al. 2006). This practice allows gene flows between wheat species, reduces the risk of breakdown due to diseases or other stresses, and increases the nutritional value of the production (Bekele 1984; Worede 1997). Geleta et al. (2009) identified two *Triticum turgidum* L. landraces carrying genes introgressed from emmer wheat and being partially free-threshing. In the Tigray region (northern Ethiopia) emmer wheat is cultivated with other wheat species or other cereals in the proportion 1:2–1:1. Sometimes, emmer is cultivated with another wheat and barley in the proportion of 1:2:2, mainly to increase the food values of end products (D'Andrea and Haile 2002). However, bread wheat-based extension programs coupled with the problem of threshability in emmer wheat has resulted in a decline of emmer production in the southeast highlands of Ethiopia. Sinana Agricultural Research Center of the Oromia Agricultural Research Institute undertook the improvement of emmer in the early 1990s for the highlands of Bale and Arsi. Currently, two improved varieties with the name 'Sinana-1' and 'Lemesso' have been released for the farming community in Bale and Arsi highlands.

Emmer wheat is cultivated in Yemen under the folkname of 'Alas' (Flaksberger 1925; Dorofeev et al. 1979; Wood 1997; Mehra 2003) and is highly appreciated by farmers for its rusticity and suitability to poor soils and drought prone conditions (Al Hakimi et al. 2008). Recent field surveys found that, beside the hulled wheat emmer 'Alas' (also called 'Bur Baladi'), there is a high diversity of emmer landraces called 'Bur Wassani', 'Bur Arabi', 'Bur Bawni' or 'Bur Harqadi', that are free-treshing. The reasons why these landraces are easily treshable remain to be discovered but may explain why emmer is still highly cultivated in Yemen for human consumption (Al Hakimi et al. 2008). The Genetic Resources Center, Faculty of Agriculture, at Sana'a University is crossing emmer wheat to durum cultivars, in order to develop new cultivars which are being tested under Yemeni rainfed conditions (Al Hakimi 1998, 1999, 2000). There was no mention of emmer from the Arabian Peninsula outside of Yemen in the litterature until a landrace with the folk name 'Alas' was reported in Oman at the end of the twentieth century (Guarino 1990). Hammer et al. (2004, 2009) recently confirmed the cultivation of emmer in Northern Oman.

In India, emmer wheat was reported to be grown in Gujarat, Maharashtra, Andhra Pradesh, Tamil Nadu, Karnataka (Howard and Howard 1910; Bhatia 1938; Mithal and Kopper 1990) and Rajasthan (Damania 1998). Today, emmer accounts for 2% of the total wheat area and production is around 250,000 tons, with the main regions of production being northern Karnataka, southern Maharashtra, the Saurashtra region of coastal Gujarat, and parts of Tamil Nadu and Andhra Pradesh (Hanchinal et al. 2005). Its persistence in these areas may be due to its resistance to rust diseases (Bhagwat et al. 2002; Hanchinal et al. 2005). Some farmers grow it under irrigated conditions particularly after sugarcane because of its high level of rust resistance as well as its capacity to ensure stable yields under a wide range of sowing dates. Most cultivation is of tall local landraces and on the local market emmer wheat gets a 40% higher price than bread wheat (Misra, personal communication). The first systematic selection of emmer wheat was carried out at the Indian Agriculture Research Insitute in Wellington, in the 1950s. Three emmer wheat varieties, selected from landraces from the Rishi Valley (Andhra Pradesh) were released at the national level under the names of 'NP-200', 'NP-201' and 'NP-202' (Nayeem and Sivasamy 2004). These cultivars were tall and had low productivity (Hanchinal et al. 2005). Newer emmer improvement efforts in India have been more successful. A dwarf mutant of 'NP-200', called 'HW1095', was further created by mutagenesis at the Bhabha Atomic Research Center (BARC) at Mumbai and found to be very productive in Gujarat, Karnataka, Maharashtra and Tamil Nadu (Nayeem et al. 2006). In the 1980s, Agharkar Institute at Pune developed a free-threshing semi-dwarf emmer wheat cultivar, 'MACS 2574'. Two varieties, 'DDK 1001' and 'DDK 1009' were then released in 1996 and 1999, respectively, by the University of Agricultural Sciences at Dharwad, by crossing local emmer wheats to durum wheat cultivars 'Raj 1555' and 'Altar 84', respectively (Nagarajan 2004; Hanchinal et al. 2005). The emmer cultivars 'DDK 1025' and 'DDK 1029', developed by using semi-dwarf emmer lines, were released by the University of Agricultural Sciences at Dharwad in 2006 and 2007, respectively. In 2009 a semi-dwarf emmer wheat cultivar, 'MACS 2971', was released by Agharkar Research Institute for the Peninsular Zone of India and another cultivar, 'MACS 2981', developed by induced mutagenesis, ranked first in the Peninsular Zone during 2006–2007 under national trials (Misra, personal communication).

Emmer wheat has also been introduced and cultivated in the New World (Stallknecht et al.

1996). Several thousand hectares of emmer were grown throughout the Midwest and western states of USA in the early 1900s (Martin and Leighty 1924). Presently, limited amounts of spring emmer are grown in scattered areas throughout Montana and North Dakota. Two unidentified emmer selections, 'Cenex emmer' and 'Common emmer' are grown and available in limited quantities from a small number of seed grain dealers (Stallknecht et al. 1996).

Genetic diversity

Emmer wheat exhibits a wide variety of forms that is likely due to its long cultivation in a large range of eco-geographical conditions (Dorofeev et al. 1979). Vavilov (1964b) already distinguished between very early accessions (particularly those from Yemen and India) and late accessions from the mountainous regions of Western Europe. Dorofeev et al. (1979) noted that most emmer wheat landraces are spring types, except some from Western Europe. Gasrataliev (1982) reported significant variation for agro-morphological traits in cultivated emmer wheats from Dagestan. Damania et al. (1990) found a wide variation for tillering, grain protein content, and resistance to common bunt and yellow rust among accessions from Ethiopia, Jordan and Turkey. Wang et al. (2007) evaluated eight agronomic characters and analyzed the relationships among 91 cultivated emmer wheat accessions from different origins; a wide range of diversity was reported but no correlation between diversity and the geographical origins of materials.

Other diversity studies have been carried out using different types of molecular markers. Švek et al. (2005) estimated relationships among 22 emmer wheats from various European countries and from the Near-East using RAPD markers. Samples from Slovakia, Yugoslavia, Turkey, Ethiopia and India were grouped in one cluster corresponding to the subsp. *asiaticum* and *abyssinicum*; within this cluster, Slovak emmers looked closely related to *serbicum* emmers from Yugoslavia. Other European accessions formed a second cluster together with accessions from Morocco and Israel, and Iranian accessions were found intermediate between these two clusters. Al Khanjari et al. (2007) analyzed genetic diversity in emmer wheat populations from Oman, using 29 SSR or microsatellite markers which could distinguish accessions from different origins (Dakhilia, Sharqia, Batinah and Dhofar districts). Genetic diversity was investigated by Teklu et al. (2007) in 73 accessions of emmer wheat from 11 geographical regions using a set of 29 SSR markers. Diversity in this study was highest in materials from Iran, Morocco and Armenia, and lowest in Yemen and Slovakia.

Uses of emmer wheat

Emmer is currently mainly used as a human food, although it is also used for animal feed. In Russia it was largely used to feed chickens (Zhukovsky 1964); in Yugoslavia, mainly as fodder for horses and pigs (Borojević 1956); in Germany, Italy, Switzerland and France as fodder for horses (Gadea 1954) and in the USA for cattle raised in feedlots (Stallknecht et al. 1996).

Ancient Egyptians mainly used emmer wheat for making a variety of breads (Samuel 1994). Loaves which have been studied with microscopy show evidence for baking with malted grain, and emmer grain was also used for beer (Drenkhahn 1975; Kemp 1989). In Roman Italy emmer wheat was used for making bread as well as *puls* (porridge) and *alica* (groats) (Braun 1995), and is still used in Tuscany as whole grains (*farricello*) in traditional soups. Its use for making pasta is a recent response to the health food market. Emmer bread (*focaccia*) can also be found in bakeries in some areas. In Asturias, emmer wheat is used to make *panchón* (bread), *formigos* (bread crumbs, eggs, milk and sugar fried and sprinkled with wine), *freixuelos* (pancake) and baby foods (*faricos*, *farinas*, *farrapes*) (Peña-Chocarro 1996). In Russia and Central Asia, it is mainly used to make *kasha* (porridge) (Boguslavskij et al. 2000). In Ethiopia emmer wheat is used today to prepare *defo* or *dabo* (bread), *budena* or *injera* (flat pancake bread), *marka* (porridge), *ambasha* or *kita* (flat steamed bread), *mullu* (boiled grain), *aka'i* (roasted grain) and *kinche* (boiled coarse grain) (Geleta, personal communication). It is fermented to prepare drinks like *farso* (beer) and *arake* (liquor) (Geleta, personal communication). In the Bale highlands, it is also used to prepare *cankita* (local spaghetti) (Tesfaye 2000; D'Andrea and Haile 2002; Geleta et al. 2009). In Yemen, emmer bread is still the most appreciated in Sanaa, as it was already the case ten centuries ago as reported by the historian, geographer and poet Abfi Muhammad Al-Hasan Al-Hamdani (893–945 AC) (Serjeant 1974). In South India, emmer wheat is commonly used for the preparation of various traditional products like *godi huggi* (polished grains cooked, mashed and heated over a low fire), *gulladiki laddu* (fried wet gluten balls), roasted *madeli* (roasted fine semolina), *holige* or *pooran poli* (dough stuffed with cooked and ground chickpea), *sajjaha* (roasted coarse semolina), *uppuma* or *upma* (roasted and seasoned coarse semolina), *rava idli* (roasted and seasoned fine semolina, fermented and steamed) and *chiroti* (fried stiff dough of very fine semolina) (Patil et al. 2003; Hanchinal et al. 2005). It is also used to elaborate pasta products (Tandon and Hanchinal 1992). Emmer products are also becoming popular in USA and Canada, particularly for speciality breads (Singh 2006).

Grain characteristics and pasta and bread-making quality

Emmer wheat is characterized by high protein and mineral concentrations. Jakubziner and Pokrovskaya (in Dorofeev et al. 1979) reported a high variation for protein content in emmer wheat. Further studies indicated that grain protein concentration can reach 18–23% (Blanco et al. 1990; Dhaliwal 1977; Pandey and Rao 1987; Perrino et al. 1993; Damania et al. 1992; Cubadda and Marconi 1994; Stehno 2007).

Semolina yield was found to be similar in emmer and durum wheat (Buvaneshwari et al. 2005). Grain hardness, which is related to the degree of adhesion between starch and proteins and influences milling quality and semolina yield, was found to be lower in emmer wheat than in durum and bread wheat (Vatsala and Haridas Rao 1990; Hanchinal et al. 2005). Dorofeev et al. (1979) reported a high variation of gluten content with the highest values present in accessions from the Indian subcontinent, Iran, Morocco, Transcaucasia and Italy. Piergiovanni et al. (2009) found higher dry gluten content in the emmer cultivar 'Farvento' than in durum and bread wheat. A high variation can be found for gluten strength, but SDS volumes up to 66 ml were found in some emmer accessions (Blanco et al. 1990; Perrino et al. 1993).

Information on the rheological properties, and baking and pasta-making, is scarce. Emmer wheat has an acceptable pasta quality that includes low stickiness, sufficient firmness and dark color (Cubbada and Marconi 1996). Gliadins ω35 and γ45, associated with pasta quality, can be found in Indian emmer cultivars like 'DDK-1001', 'DDK-1009' and 'DDK-1013' (Buvaneshwari et al. 2005). Le Clerc et al. (1918) indicated that emmer wheat can be used for making bread, but with lower quality than *T. aestivum*. This is largely due to a lower loaf volume (Piergiovanni et al. 1996). However, Grausgruber et al. (2004) reported a large variation for rheological properties of emmer wheat. Degaonkar et al. (2005) analyzed the storage protein composition of 61 accessions of emmer wheat by SDS–PAGE (HMW- and LMW-glutenin subunits) and acid-PAGE (gliadins), and detected the presence of HMW subunits like 13 + 16, 2 and 1, associated with good bread making quality.

Historically, emmer grain and flour are appreciated for their sensorial qualities. Experiments and surveys carried out by Filatenko et al. (1983) and Boguslavskij et al. (2000) show that *kasha* prepared from emmer wheat is friable, and has a very appealing smell and taste. In India, taste and flavor of most traditional foods is recognized to be better when they are prepared with emmer wheat than with durum and bread wheat (Hanchinal et al. 2005). This is likely to be due the higher concentration in emmer grain of total and non-reducing sugars (Reddy et al. 1998). Similarly, in Yemen, consumers still prefer emmer wheat for many traditional foods such as flat breads, *harish* or *chorba* (Al Hakimi et al. 2008). Bread has better flavor, taste and crust color when made with emmer wheat than with bread wheat (Cubadda and Marconi 1994).

Emmer wheat as health food

In Ethiopia, the Oromo ethnic groups have many traditional songs and sayings that emphasize emmer′s medicinal value and food quality (Asfaw 1990; Geleta et al. 2009). Emmer wheat is recommended for mothers as a special diet in maintaining their health and strength after childbirth. It is also recognized as a suitable food for children (Geleta, personal communication). Farmers appreciate emmer as compared to other wheat because it does not affect the stomach when consumed in any form and is considered to be healthy food (Tesemma and Belay, 1991).

Information about emmer grain composition and nutritional value, however, is scarce and sometimes controversial.

Similar amino-acid composition was reported in emmer and bread wheat (Cubadda and Marconi 1996). Higher lysine content (up to 3.65%) was reported by Stehno (2007) in the Czech emmer cultivar 'Rudico'. Fat content in emmer ranges from 1.02 to 3.80% (Hanchinal et al. 2005). Crude fiber content is higher in emmer than in durum wheat (Annapurna 2000). Mineral content was found by Hanchinal et al. (2005) to range from 1.14 to 2.46% and to be lower than in durum wheat, although Cubadda and Marconi (1996) reported higher ash content in an emmer landrace from the Garfagnana region and Piergiovanni et al. (2009) reported higher mineral content in the emmer cultivar 'Farvento'. 'Farvento' grains also had higher concentration in selenium, an important antioxidant factor. Genc and MacDonald (2008) identified domesticated emmer wheat accessions with greater grain zinc concentration than modern durum and bread wheat genotypes. Ortiz-Monasterio and Graham (2000) reported high zinc concentration in the accessions PI254187 (selection in the landrace 'Amarello de Barba Branca' from Portugal) and PI94677 (landrace from the Krasnodar Ostrada Province, Russia). In Yemen, large genetic variation was found in among the Yemeni landraces 'Arabi' and 'Samra' from Al-Arafah, 'Wasani' from Saber (Taizz) and 'Khashabi' from Bani Matar (Sanaa) for proteins and minerals concentration (Al Hakimi, personal communication).

The nutritional value of emmer wheat, confirmed by some medical data (Strehlow et al. 1994; Italiano and De Pasquale, 1994), is mainly due to its high fiber and antioxidant compound concentrations (Piergiovanni et al. 1996), high protein digestibility (Hanchinal et al. 2005) and high resistant-starch content and slower carbohydrates in vitro digestibility (Mohan and Malleshi 2006). The low glycaemic index value and high satiety value of emmer wheat make it particularly suitable for diabetes (Buvaneshwari et al. 2003). Most of these qualities are related to a higher total dietary fiber (Yenagi et al. 1999; Annapurna 2000; Hanchinal et al. 2005), which is associated with a reduced rate of starch digestion (Jenkins et al. 1984). Substitution of bread wheat by emmer wheat in the diet for 6 weeks led to a significant reduction of total lipids, triglycerides and LDL (low-density lipoprotein) cholesterol. Emmer wheat is actually used in India in the preparation of instant *uppama* for diabetes (Annapurna 2000) and pasta for endurance athletes (Kavita 1999).

The antioxidant qualities of emmer could be due to different types of non-specific lipid transfer proteins (nsLTPs), compared to bread wheat. Bread wheat contains the 9 kDa nsLTPs, while emmer possesses the 7 kDa nsLTPs (Capocchi et al. 2005). Serpen et al. (2008) evaluated einkorn and emmer wheat accessions for antioxidant activities and found significantly higher amounts of total antioxidant activity, total phenolics, ferrulic acid and flavonoids in emmer wheat accessions. However, emmer grain has lower β-carotene than bread and durum wheat (Abdel-Aal et al. 1998; Handelman 2001; Hughes 2001). Carotenoid concentration in tetraploid wheats from Ethiopia was found to vary from 1.5 to 1.9 ppm (Hailu and Merker 2008) which is half that found in durum wheat.

Little is known about anti-nutrients in emmer wheat. Cubadda and Marconi (1996) found higher phytic acid concentration than in bread wheat, but similar trypsin inhibitor content.

Toward a development of emmer wheat cultivation and use?

Considering increasing requirements for richness, diversity and high quality of foodstuff products, the interest for emmer wheat is increasing. Such a renewed interest has its origin mainly in countries with well-developed intensive agriculture (Hammer and Perrino 1995; Nielsen and Mortensen 1998; Olsen 1998). Italy offers a good example of new development of emmer wheat cultivation (D'Antuono 1994). Starting in 1994, multi-year national tests to compare ecotypes of *farro* were initiated by the CERMIS (Centro Ricerche e Sperimentazione per il Miglioramento Vegetale 'N. Strampelli') in various locations in Italy (Castagna et al. 1995; Porfiri et al. (1996)). Other research was conducted by the Italian Ministry of Agriculture (Mariani et al. 1992a, b). Finally, there have been a series of initiatives by farmer's co-operatives and producer's associations aimed at growing *farro* as an alternative crop. The first collaboration in Italy on this topic involved the former Istituto del Germoplasma (IG, now Istituto di

Genetica Vegetale, IGV) of CNR (Consiglio Nazionale delle Ricerche) in Bari and an agricultural co-operative situated in the Molise region (Perrino et al. 1991, 1993). A similar initiative is underway involving IGV and the APROCEL Consortium located in the region of Basilicata (Perrino et al. 1996; Laghetti et al. 1997). In the mountainous Garfagnana area of Tuscany, emmer is now grown by farmers as an IGP (*Indicazione Geografica Protetta*) product, with its geographic identity protected by law. Production is certified by a co-operative body, the *Consorzio Produttori Farro della Garfagnana*. IGP-certified *farro* is widely available in health food shops across Europe. Recently, the renewed interest for emmer was illustrated by the establishment of a varietal register (Pagnotta et al. 2009). Emmer wheat cultivars 'Yakub', 'Rossorubino', and 'Zefiro' have been recently selected from landraces while modern cultivars 'Davide', 'Mose', and 'Padre Pio' have been obtained by crossing cultivated emmer to durum wheat (Codianni et al. 2000; De Vita et al. 2006). Today, the main production areas of emmer are Garfagnana, Valneriana and Altopiano di Leonessa, alte Valli del Tronto and dell'Aterno, valle dell'Aniene, alto Molise, Appennino Dauno and Appennino Lucano (Porfiri et al. 1998). Due to its low input requirements (Laghetti et al. 1998) and its high level of resistance to stem rust, leaf rust and powdery mildew (Corazza et al. 1986) it is mainly grown in organic farming (Tallarico 1990). In many cases it is a valid economic alternative to durum wheat, mainly for its lower production costs (Tallarico 1990; Perrino and Laghetti 1994). Whole emmer grains can be easily found in most Italian supermarkets and groceries, and a new flourishing market for products based on *farro* has emerged (D'Antuono, 1995). Similarly, in the Czech Republic, the cultivar 'Rudico', resistant to most fungal diseases such as powdery mildew and septoria and recommended for organic farming, gained a certificate of legal protection after 3 years of testing (Stehno 2007).

Useful traits and potential interest for durum and bread wheat breeding

Resistance to leaf diseases and common bunt were found by Vavilov (1964b), Jakubziner (1969) and Dorofeev et al. (1979) to highly depend on the subspecies, convariety and proles. Results of their evaluations have been compiled by Dorofeev et al. (1987) (Table 2).

Resistance to rusts in emmer wheat accessions has also been reported by Gasrataliev (1983) and Bennett (1984). Corazza et al. (1986) evaluated emmer landraces collected from the mountainous areas of Central Italy for resistance to stem rust, leaf rust, and yellow rust. Mithal and Kopper (1990) identified rusts resistant landraces in the Punjab province in India. Outstanding sources of resistance to stem rust *Puccinia graminis* Pers. f. sp. *tritici* Eriks. et E. Henn. were found in emmer wheat. Jakubziner (1969) noted that 'Khapli', an Indian emmer accession, was immune to stem rust. Williams and Gough (1965) indicated that four genes controlled the seedling reaction of 'Khapli' and three were identified tentatively as *Sr7*, *Srl3*, and *Srl4*. Stem rust resistance was also found in the accession PI94701 from Palestine (Rondon et al. 1966) and the landrace 'ST464' (PI191365) from Ethiopia (Lebsock et al. 1967). Beteselassie et al. (2007) evaluated seedlings of 41 emmer wheat accessions for their response to stem rust infection under greenhouse condition and selected 18 accessions as sources of resistance. Resistance to yellow rust has also been reported in 18 accessions of emmer wheat belonging to the ICARDA genebank collection (Damania and Srivastrava 1990).

Reed (1916) identified the landrace 'Khapli', from India, as immune to powdery mildew, *Blumeria graminis* (DC.) Speer. Immunity to powdery mildew was also reported by Vavilov (1964b) and Jakubziner (1969) in accessions from Europe and Dagestan, respectively. Resistant accessions are generally found in the ssp. *abyssinicum* and *europeum* and in the convar. *serbicum* (Dorofeev et al. 1979). A dominant gene for resistance to the powdery mildew fungus, designated as *Pm4*, was transferred by Briggle (1966) from 'Khapli' into the genetic background of the hexaploid wheat variety 'Chancellor'.

Emmer wheat resistance to *Ustilago tritici* (Pers.) Rostr. was reported by Michalikova (1970) and Krivchenko (1984). The most susceptible accessions belong to the *abyssinicum* group and the most resistant to the convar. *serbicum* (Yamaleev et al. 1975). Emmer wheat has also been considered as a source of resistance to fusarium head blight or scab (*Fusarium graminearum*) (Oliver et al. 2008), tan spot (*Pyrenophora tritici-repentis* (Died.) Drechs.), and Septoria blotch (*Stagonospora nodorum*) (SNB) (Chu et al. 2008). It also showed resistance to Russian Wheat Aphid (*Diuraphis noxia*) (Robinson and Skovmand 1992; Liu et al. 2005) and Hessian Fly (Zhukovsky 1964).

Multitraits evaluation of cultivated emmer wheat in Ukraine showed that emmer wheat could be a valuable source of useful traits for durum wheat breeding, like earliness and resistance to common bunt, leaf rust, powdery mildew and septoria (Boguslavskij et al. 2000). Evaluations of tetraploid wheat accessions from Ethiopia also allowed identifying emmer accessions with high thousand kernel weight, spike density and protein content (Beteselassie et al. 2007; Hailu and Merker 2008).

Emmer wheat has also proven to be a valuable source of useful agronomical traits like tillering or grain weight. The presence of the *Rht-B1b* allele in the cultivar 'DDK 1009' and some semi-dwarf mutant lines, proven by their insensitivity to GA_3, can be used as alternate dwarfing source other than 'Norin-10' (Bhagwat et al. 2006). Finally, some emmer populations have proven to have tolerance to drought (Zhukovsky 1964; Damania et al. 1992; Al Hakimi and Monneveux 1997) and heat (Hanchinal et al. 2005). Drought and heat tolerance should be preferentially searched in the ssp. *asiaticum* and *maroccanum* (Dorofeev et al. 1979). One variety of Indian emmer wheat was found by Hunshal et al. (1990) to yield more than barley under a number of salinity levels.

A study of interspecific hybrids realized by Yanchenko (1985) emphasized the complete genomic compatibility between emmer and durum wheat. In another study, carried out in Dagestan, progenies of crosses between durum and emmer wheats were evaluated for earliness, plant height, 1,000-kernel weight, and productive tillering (Gasrataliev 1982). Although the typical emmer traits of persistent glumes and ear brittleness are not entirely eliminated from the progeny, their effects can be reduced to commercially acceptable levels.

Conversely, hybrid necrosis and hybrid chlorosis are frequently met with in crosses between emmer and bread wheat (and more generally between tetraploid and hexaploid wheats) and are serious barriers to genes transfer. Hybrid necrosis is governed by two complementary genes, *Ne*1 and *Ne*2, *located* on chromosomes 5B and 2B, respectively (Tsunewaki 1960) while hybrid chlorosis is controlled by two complementary genes *Ch*1 located on 2A (Hermsen and Waninge 1972) and *Ch*2 on 3D (Tsunewaki and Kihara 1961). Hermsen (1966), Kochumadhavan et al. (1984) and Tomar et al. (1991) reported that the gene *Ch*1 widely occured amongst the Indian varieties of cultivated emmer.

Emmer wheat has been largely used in the creation of popular bread and durum wheat cultivars. The stem rust resistant bread wheat cultivars 'Hope' and 'H-44' resulting from the cross between the rust resistant 'Yaroslav emmer' and the bread wheat cultivar 'Marquis' (McFadden 1930) have been extensively utilized in US breeding programs. The gene *Sr2* transferred from 'Yaroslav emmer' to bread wheat can confer slow rusting (Sunderwirth and Roelfs, 1980). In addition to other unknown minor genes derived from 'Hope' and 'H-44' and commonly known as *Sr2*-complex, it provided the foundation for durable resistance to stem rust in bread wheat. 'Hope' and 'H-44' participated, for example, in the pedigree of the winter bread wheat cultivars 'Ottawa', 'Langer', 'Jage', 'Scout 66', 'Talbot' and the spring bread wheat cultivars 'Apex', 'Regent', 'Renown' (Canada), 'Rival', 'Pilot', 'Vesta', 'Mida' and 'Nenthatch' (USA) (Dorofeev et al. 1987).

Genes for resistance to race *15B* identified in the Indian emmers 'Khapli' and 'Vernal' have also been used widely in durum breeding (Heermann 1960; Ataullah 1963). 'Khapli' has been used as parent to develop the durum wheat cultivars 'Langdon' (Heermann and Stoa 1956) and 'Wells' (Heyne 1962) as well as 'Yuma', 'Lakota' (USA) and 'Bezentchukskaya 115', 'Leucurum 19', 'Leucurum 54', 'Kharkovskaya 46', 'Kharkovskaya 51', 'Hordeiforme 230', 'Almaz' and 'Raketa' (USSR) (Dorofeev et al. 1987). Stem rust resistance genes coming from 'Vernal' were first introgressed into 'Mindum' (Smith 1957). They are also present in the durum wheat cultivars 'Stewart', 'Vernum', 'Carleton' (USA) and 'Hercules' (Canada). The emmer landrace 'ST464' (from Ethiopia) was the source of rust resistance genes in 'Leeds' (Lebsock et al. 1967). The durum wheat cultivar 'Ward' includes in its pedigree the sources of stem rust resistance 'Vernal', 'Khapli' and 'ST464' as well as the accession CI17780 from Ethiopia (Quick et al. 1974).

More recently, cultivated emmer has been used at CIMMYT (Centro Internacional de Mejoramiento de Maiz y Trigo, Mexico) to produce new (emmer based) hexaploid synthetic wheats and synthetic backcross derived lines. Synthetic hexaploid wheats, obtained by crossing durum wheat (BA- genomes) with the diploid goatgrass *Aegilops tauschii* Coss. (syn. *Ae. squarrossa* L.), as described by Mujeeb-Kazi et al. (1996), have already allowed a significant increase of bread wheat (BAD-genomes) genetic diversity (Warburton et al. 2006). However, cultivated emmer exhibits higher genetic diversity compared to durum wheat (Dreisigacker et al. 2008), as well as drought and heat tolerance. Consequently, some hexaploid synthetic wheats have been generated at CIMMYT using emmer wheat as a female parent and backcrossed to elite bread wheat cultivars to produce agronomically acceptable synthetic backcross derived lines. Emmer based synthetic backcross derived lines were found to have a high level of resistance to greenbug (Lage et al. 2003) and Russian wheat aphid (Lage et al. 2004) as well as good grain quality (Lage et al. 2006). Emmer based synthetic backcross derived lines also showed higher yield under drought-prone conditions in Mexico, Pakistan and Eastern India compared to those using durum wheat (Trethowan and Mujeeb-Kazi 2008).

A research project involving CIMMYT (Mexico) and national institutions from India (Agharkar Institute at Pune and Dharwad University), Australia (Sydney University) and Pakistan (Pakistani Agricultural Research Center, PARC) and funded by the GCP (Generation Challenge Programme) has consequently been initiated to discover novel and useful genetic diversity from emmer wheat and transfer it into elite bread and durum wheat background by direct crosses and new synthetic wheat production. As a component of this project, a large collection of 300 well-documented emmer wheat accessions, originating from 35 countries, covering the area of distribution of the species, has been established at CIMMYT, evaluated for a large range of morpho-physiological traits and its diversity assessed using Simple Sequence Repeat (SSR) and Diversity Array Technology (DArT) markers (Zaharieva et al. 2009). The more diverse and promising accessions, with good agronomic performance are being used to develop new pre-breeding germplasm available to be used in breeding programs worldwide.

Conclusion

Emmer wheat, a minor cereal today, should know a new development due to the nutritional value of its grain, the special taste of its products, and its characters of resistance to pests and disease that can be easily transferred to durum and bread wheat.

The valorization of emmer products (bread, pasta) with high nutritional value (content and quality of gluten and lower allergy reactions) and specific taste and flavor has permitted to maintain (e.g. India) or even develop (e.g. Italy) the cultivation of emmer wheat in some regions. Additional advantages of emmer wheat are some agronomic aspects (high tillering, tolerance to abiotic and biotic stresses, suitability to marginal lands) connected to conventional, low input and organic crop systems,

Based on successful experiences it, however, appears that further increases in emmer wheat cultivation and production would require a well-organized, completely clear, transparent and traceable production chain. To achieve this, farmers would have advantage to cultivate landraces in traditional cultivation area, following adapted cultivation system and realizing the cultivation under agreement with transformers. Transformers might privilege local varieties, highlight the links of products with territory and its history, prioritize final products with high qualitative organoleptic and nutritional traits and promote the cultivation under agreement with farmers. Traders should promote marketing actions which exploit the local production and safeguard the local market against the global market.

Further development of emmer cultivation also needs better information about its qualities, research efforts that include selection and multi-local and multi-year testing, legal protection of geographic identity and establishment of a varietal register. Adaptation of emmer wheat to low fertility and organic farming conditions and its low production costs must be taken into account to define the agro-ecological conditions and cropping systems where it can represent a valuable alternative to durum or bread wheat.

On the other hand, the use of emmer wheat as a reservoir of genes for improving bread and durum wheat has been quite successful. The tremendous gains in wheat production associated with the so-called green revolution in India and Pakistan would probably not have been realized without the protection of the *Sr2* gene originated from emmer wheat. The traits of resistance to rusts and powdery mildew as well as tolerance to heat and drought present in emmer wheat can be of interest in the context of climate change. These traits can be introgressed easily into bread wheat either by direct crosses, or by using emmer as a female parent to create synthetics hexaploid wheats that can be re-crossed to elite bread wheats.

The genetic erosion which affected this species and its complete disappearance in some countries can, however, endanger its genetic diversity. Many landraces have been collected some decades ago, when emmer wheat was more widely cultivated, but passport data information is generally poor. Genetic diversity of emmer wheat has generally been studied at a regional level only. Efforts are consequently now required to establish well-documented collections and analyze genetic diversity at a worldwide level. An increasing interest from the scientific community is required for extending collection, conservation and evaluation of genetic resources, developing studies about genetics (genetic diversity between and within different populations, genetic links with other cereal species, identification of useful genes for interesting traits) and develop core-collections that will facilitate evaluation for useful agronomical and nutritional traits.

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