Chapter 1

Sorghum and Foxtail Millet—Promising Crops for the Changing Climate in Central Europe

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Abstract

Climate change is connected to many undesirable aspects which may strongly affect agricultural production in the future, not only in the Czech Republic but also in other countries in Central Europe. The most serious risks with the main impacts on agricultural production are the frequency and intensity of occurrence of extreme events. Problems caused by drought and its impact on agricultural production are starting to be serious and urgent. One of the solutions is using the drought-tolerant/resistant species and/or varieties more adaptable to water stress. Sorghum and foxtail millet might be the solution for Czech conditions. They can provide good yields even in dry periods. This study discusses grain quality of foxtail millet and biomass quality in the case of sorghum. In addition, the benefits of cultivation of these two species and current knowledge from a scientific point of view are summarised here.

Keywords: sorghum, foxtail millet, genetic resources, alternative crops, biomass production

1. Current situation

Climate change is connected to many undesirable aspects which may strongly affect agricultural production in the future, not only in the Czech Republic but also in other countries in Central Europe. The main signs of these changes are a lack of water, extreme fluctuation of weather, movement of vegetation, and floods. The most serious risks are then the frequency and intensity of occurrence of extreme events. The main impacts on agricultural production are declines in yield, increased crop failure, change in the geographical distribution of some plant species, the occurrence of invasive species, thermophilic diseases and pests, etc. Problems caused by drought and its impact on agricultural production are starting to be serious and urgent. In the Czech Republic, the most outstanding period of drought was recorded in 2012. In the region of South Moravia (part of the Czech Republic), the yield of winter wheat was lower by 22.8% in comparison with 2011. Czech agriculture faced a similar situation in 2015. Because these situations may repeat in the future as well, the Agrarian Chamber of the Czech Republic and the Ministry of Agriculture issued a recommendation and long-term system actions leading to the involvement of the state in solving these situations in the future. One of the recommendations is using non-technical measures, such as breeding and selection of drought resistant species and varieties more adaptable to water stress and more resistant to changing climate conditions.

Sorghum and foxtail millet might be the solution for Czech conditions. Research on the suitability of both mentioned species in the Czech Republic has been carried out at the Crop Research Institute (CRI) since the 1990s. The main aim is to evaluate and select suitable genotypes of sorghum and foxtail millet for human consumption, which may be an alternative to grain and for biomass production for arid areas of the Czech Republic as well as other countries in Central Europe. Both of these crops belong to the C4 species, which can better manage water through photosynthesis. They can provide good yields even in dry periods. This study discusses grain quality of foxtail millet and biomass quality in the case of sorghum. In addition, the benefits of cultivation of these two species and current knowledge from a scientific point of view are summarised here.

The group of millets refers to a number of different species such as *Panicum miliaceum* L., *Pennisetum glaucum* (L.) R.Br., *Setaria italica* (L.) P. Beauv. [1] early together with sorghum (*Sorghum bicolor* L.), and even maize (*Zea mays* L.). Millets and sorghum belong to the oldest cultivated crops, which have been very important staples and ethnobotanical crops in the semi-arid tropics of Asia and Africa for centuries [2, 3]. The millets and sorghum are various grass crops that are harvested for human food, animal feed, and medicinal purposes [4]. Sorghum is the fifth most important cereal in the world after wheat, rice, maize, and barley. Some 49 and 55% of the world's millet and sorghum cultivation areas, respectively, are in Africa. In India, millet is said to constitute the fourth most commonly grown cereal, following rice, wheat, and sorghum [5]. Although sorghum and millets account for about the same total production as maize, they account for nearly twice the cultivated area [1].

Foxtail millet and sorghum are high energy [6], nutritionally equivalent or superior to other cereals [7], and do not contain gluten-forming proteins. Sorghum is also a potentially important source of nutraceuticals such as antioxidants, phenolics, and cholesterol-lowering waxes [8]. Foxtail millet and sorghum play a significant role in food security for developing countries in Asia and Africa and also play a growing role in processing and new alternative products for the developed world [7]. They are of value especially in semiarid regions because of their short growing season and higher productivity under conditions where another cereal crops may fail [9]. Compared to other cereals, millets are mainly suited to less fertile soils and poorer growing conditions, such as intense heat and low rainfall [4, 9].

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2. Introduction

2.1. Foxtail millet

Foxtail millet [*Setaria italica* (L.) P. Beauv.] is one of the oldest cereals in Eurasia [10], grown since 5000 BC in China and 3000 BC in Europe. It probably evolved from the wild green foxtail millet—*Setaria viridis* (L.) P. Beauv. [11–13]. The geographical origin of foxtail millet is still a controversial issue [14]. Its domestication could have taken place anywhere across its natural range extending from Europe to Japan, perhaps even several times independently; it was most probably first domesticated in the highlands of central China, from where it spread to India and Europe soon thereafter [11, 15]. At present, foxtail millet is cultivated all over the world, being most important in China, India, Indonesia, the Korean peninsula and south-eastern Europe [16]. In most countries in the world, foxtail millet is cultivated mainly for production of grains for human consumption. The tiny grains are milled into flour used for preparation of different dishes (puree, cakes, etc.). In China, Korea, and Japan, foxtail millet is important for beer preparation, with the sprouted seeds used instead of malt. Thanks to fermentation, various alcoholic beverages are prepared [17]. In Europe, seeds of foxtail millet are used for poultry feeding and plants are cultivated as a fodder crop for green biomass or hay production.

2.2. Sorghum

The greatest diversity in both cultivated and wild types of *Sorghum* Moench is found in north-eastern tropical Africa. It is thought that the crop was domesticated in Ethiopia by selection from wild sorghum types between 5000 and 7000 years ago [18]. Doggett [19] also considered Ethiopia and the surrounding countries as a centre of domestication. From north-eastern Africa, sorghum was probably distributed all over Africa and along shipping and trade routes through the Middle East to India [20]. Sorghum probably travelled overland from India and reached China [9] and South-East Asia [20] along the silk route about 2000 years ago. It might also have gone by sea directly from Africa. Chinese seamen reached Africa's east coast more than 1000 years ago (probably in the eighth century AD), and they may well have carried some seeds home [9]. From West Africa, sorghum was taken to the Americas through the slave trade. It was introduced into North America for commercial cultivation from North Africa, South Africa, and India at the end of the nineteenth century [20]. It was subsequently introduced into South America and Australia, where it has become an established grain and fodder crop. It is now widely cultivated in drier areas of Africa, Asia, the Americas, Europe (France, Italy, and Hungary) as well as Australia, Russia, and Argentina. It is cultivated between 50°N and 30°S latitude and up to 2200 m above sea level [16, 18]. Sorghum types exclusively cultivated for the dye in the leaf sheaths can be found from Senegal to Sudan [20]. Sorghum was introduced to the Czech Republic in the 1920s when it was used mainly as a fodder crop. Until 1950, the area of cultivated sorghum was higher than the introduced new maize varieties. In the first decade of the twenty-first century, the higher interest in sorghum cultivation is connected with the development of renewable energy for power plant feeding by biomass production due to the fact that sorghum provides it in high quality and amount.

3. Morphology

3.1. Foxtail millet

Foxtail millet is an erect annual grass [11], between 0.6 and 1.2 m tall, tufted, often variously tinged with purple. Its root system is dense, with thin wiry adventitious roots from the lowest nodes [15] (**Figure 1**).

The stem is erect, slender, tillering from the lower buds, sometimes branched. Primitive cultivars have numerous, strongly branched stems, while advanced cultivars produce a single stem with a large, solitary inflorescence [11].

Its leaves are alternate, simple [11]; leaf sheath cylindrical, 10–15 (−26) cm long, glabrous or slightly hairy; ligule short, fimbriate; blade linear-acuminate, 16–32 (−50) × 1.5–2.5(−4) cm, midrib prominent [15], slightly rough [11].

The inflorescence is a spike-like panicle 5–30 × 1–2(−5) cm, erect or pendulous, continuous or interrupted at the base; the rachis is ribbed and hairy; the lateral branches are short, bearing 6–12 spikelets. The spikelets are almost sessile, subtended by 1–3 bristles up to 1.5 cm long, elliptical, usually about half as long as the bristles [11].

Its fruit is a caryopsis (grain) [11], which is enclosed in coloured hulls [11, 21, 22] with the colour depending on the variety [21]. The grain is broadly ovoid, up to 2 mm long [11]. The colour of the grain varies from pale yellow to orange, red, brown, or black [23]. Generally, foxtail millet seeds are not dormant [24]. The 1000-seed weight is about 2 g [23].

Foxtail millet has a short vegetation crop [24]; total crop duration is 80–120 days, although some cultivars only need 60 days to mature [11]. Foxtail millet is largely self-pollinating with an average outcrossing rate of 4%; natural hybrids between wild and cultivated types occur. Foxtail millet has largely lost the ability of natural seed dispersal and shows a tendency toward uniform plant maturity [11].

3.2. Sorghum

Sorghum comes in many types. All, however, are coarse, cane-like grasses between 0.5 and 6 m tall [9], depending on the variety and growing conditions [25]. Most are annuals; a few are perennials [9]. Its roots are concentrated in the top 90 cm of the soil but sometimes extending to twice that depth, spreading laterally up to 1.5 m [9, 20].

The stem (culm) is solid [20], or sometimes with spaces in pith [26], usually erect [9, 20], 5–30 mm in diameter [25]. Stems may be dry or juicy. The juice may be either insipid or sweet. Most have a single stem, but some varieties tiller profusely, sometimes putting up more than a dozen stems. These extra stems may be produced early or late in the season [9].

The leaves are alternate, simple [20], broad and coarse, looking much like those of maize [9] but are shorter and wider [25]. A single plant may have as few as 7 or as many as 24 leaves, depending on the cultivar [9]. At first they are erect, but later curve downward. During drought, they roll their edges together. Rows of 'motor cells' in the leaves cause the rolling

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action and provide this unusual method of reducing desiccation [9]. The leaf sheath is 15–35 cm long [20], often with a waxy bloom [27], with a band of short white hairs at the base near attachment, reddish in dye cultivars [20]. The leaf blade is lanceolate to linear-lanceolate, 30–135 cm long and 1.5–13.0 cm broad, initially erect, later curving, margins flat, or wavy [18].

The inflorescence is a terminal [20], more or less open panicle [28] (**Figure 2**), up to 60 cm long [20] and 5–25 cm broad [28]; the rachis is short or long, with primary, secondary, and sometimes tertiary branches, with spikelets in pairs and in groups of three at the ends of the branches [20]. Sorghum is predominantly self-pollinating [20].

The fruit is a caryopsis (grain) [20], typically thought of as round [29]. Due to the genetic diversity of sorghum, grains can vary widely in size and shape. Commercial sorghum hybrids are 4–8 mm long [20, 30], 2 mm broad [30], smaller than those of maize but with a similar starchy endosperm [9]. The grains are usually partially covered by glumes [20]; the seed coat varies in colour [9] from white [25], pale yellow through to red, purple-brown. Dark-coloured types generally taste bitter because of the tannins in the seed coat [9]. The 1000-seed weight varies from 13 to 80 g [20, 27, 30].

In the tropics and subtropics, sorghum may be one of the quickest maturing food plants [9]. Early maturing sorghum cultivars take only 100 days or less [20] and can provide three harvests a year [9], whereas in temperate areas it requires 5–7 months [20].

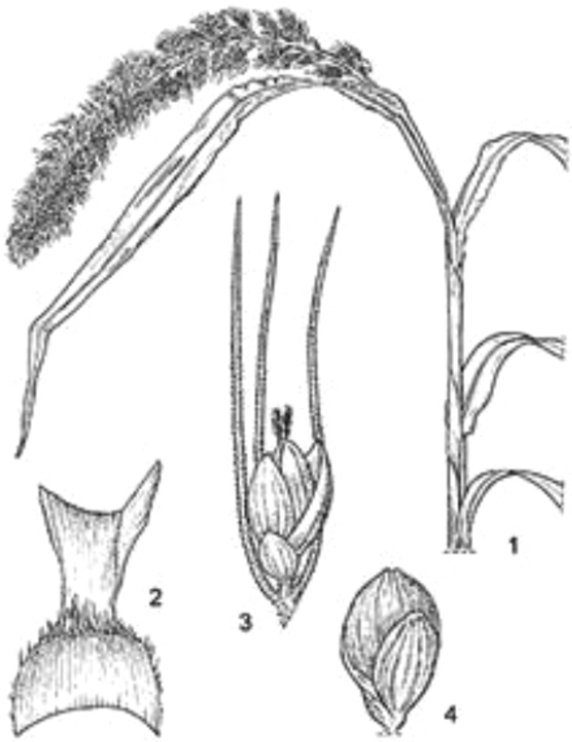

Figure 1. *Setaria italica* [11].

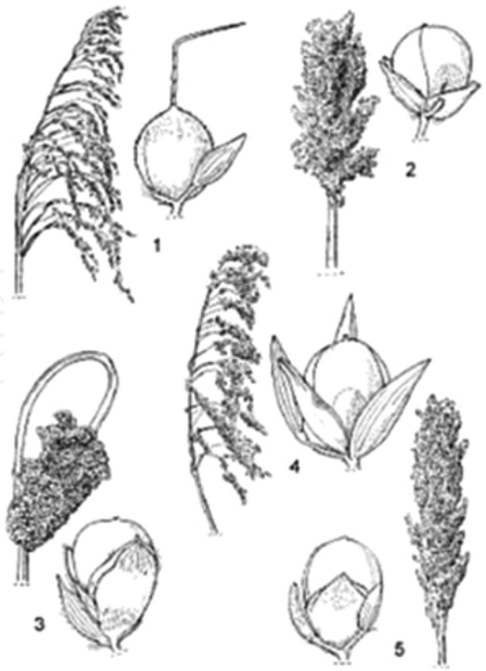

Figure 2. Panicles and spikelets of the 5 basic races of sorghum: 1—bicolor; 2—caudatum; 3—durra; 4—guinea; 5—kafir [18].

4. Breeding

4.1. Foxtail millet

Wang et al. [31] wrote the first mention of foxtail millet suitability for genetic and molecular studies due to the small genome size and its diploid nature. Genetic variability studies for the identification of trait-specific germplasm accessions for various agronomic and nutritional traits are lacking in foxtail millet, and are hence seldom used in breeding [32]. The major breeding objectives of foxtail millet are developing high-yielding cultivars which produce protein-rich seed and are resistant to diseases, pests, and lodging [33], and are adapted to local ecological conditions [15]. One of the important components of plant breeding programmes has been crop improvement through the introduction of novel genes from wild relatives [31, 34] with the research focused on salt stress responses in foxtail millet seedlings. In the Czech Republic, the breeding of foxtail millet accessions is performed by the Gene Bank of the CRI. The collection of foxtail millet includes 42 accessions in an active collection and 150 genotypes in a working collection. The main aim is to find foxtail millet genotypes as a new source of gluten-free grain, a source of feed for animals (hay and seeds) as well as for biomass production used in power plants. Based on the work with genetic resources of foxtail millet, a broad set of foxtail genotypes were chosen which were further selected (**Table 1**). The main sources of new genotypes are other gene banks, universities, or botanical gardens all over the world. Because some foxtail millet genotypes may be sensitive to daylight duration, the sensitivity to the day length is the main parameter of the evaluation. During the vegetation, several morpho-

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phenological characteristics and health assessment of plants were done. After harvest, all genotypes unsuitable for the temperate conditions of the Czech Republic were excluded from the collection. The evaluation was focused on the early-ripening genotypes, on the size of grains, as well as on production of high amount of biomass described by the plant height. In 2014, a new perspective variety of *Setaria italica* 'Ruberit' was bred in the Czech Republic suitable for the production of biomass, human consumption (corn), and livestock nutrition (grain and forage) (**Appendix I**) New genotype of *Setaria italica* 'Rucereus' bred for conditions of the Central Europe. Is now under testing of Central Institute for Supervising and Testing in Agriculture (**Appendix II**).

Year	New cultivated genotypes	Not grown up genotypes	Not flowering genotypes	Not ripening genotypes	Total no. of sown genotypes
2010	31 (37.8%)	0 (0%)	26 (31.7%)	25 (30.5%)	82 (100%)
2011	86 (86%)	0 (0%)	2 (2%)	12 (12%)	100 (100%)

Table 1. Summary of evaluation of new genetic resources of foxtail millet in the CRI, Prague Ruzyně.

4.2. Sorghum

To date, in the EU, there are 462 varieties of *Sorghum bicolor* registered. However, landraces and wild related species of sorghum are an important source of various properties for breeding, such as tolerance and resistance to pests and diseases, abiotic stresses such as lack of water and high temperature, as well as quality and nutrition content for feed, food, and technical utilisation [35]. Globally, in different gene banks, there are about 168,000 accessions of sorghum. In the USA, genetic resources from gene banks are used to create new lines of A-, B-, and R-, which then are used by private breeding companies producing new hybrid varieties. This shows the key role of the interconnection of private and public sector in the creation of new varieties [36]. To date, the International Union for the Protection of New Varieties of Plants (UPOV) has registered a total of 3951 varieties of *Sorghum bicolor* worldwide.

Sorghum is a short-day plant which uses the C4 photosynthesis system. Maturity is influenced by the length of day and temperature. Breeding starts with adapting short-day crop to conditions of the temperate zone to a longer day, and shortening the stalks for improved mechanical harvesting [36]. The most used techniques for breeding sorghum are the same as in the case of maize. Since the 1950s, the cytoplasmic male sterility (CMS) method has been used (**Table 2**).

The main objectives in sorghum breeding worldwide include high grain yield [37], resistance to major yield-limiting diseases and pests [38], drought tolerance [39–41], cold tolerance [42], and tolerance to the other abiotic stresses [43, 44]. Resistance to grain moulds [45, 46] and other diseases [20, 35, 47] as well as to insect pests [48] has been identified.

Line	Cytoplasm	Genotype	Phenotype
A-line	A	rfrf	Male sterility
B-line	N	rfrf	Male fertility
R-line	A or N	RFRF	Male fertility
Hybrid	A	RFrf	Male fertility

Table 2. Genotype and phenotype for A-, B-, and R-line in system of cytoplasmatic male sterility in; N—normal cytoplasm, A—sterility inducing by cytoplasmic [36].

In the northern part of Europe, the cultivation of sorghum has a certain tradition. In recent years, due to changing climate, sorghum cultivation has become attractive in the Central parts of Europe (Germany, Hungary, and Austria). The cultivated areas have increased and the breeding programmes of sorghum were established. They are bred for cold resistance, earliness, and decrease of anti-nutritional components in seeds [49]. It is necessary at the outset to state that a breeding programme for sorghum in the Czech Republic currently does not take place; we are merely introducing materials from countries where sorghum breeding programmes are supported.

When we select varieties of grain sorghum, those with the shortest growing season are chosen. Furthermore, a very important feature is the grain chemical composition. When grain is used for human food, the grain shape and size are important. Grain for food purposes may be depreciated and reduce the possibility of its use as a food due to high tannin content. Therefore, one of the important objectives in the context of grain sorghum breeding is to obtain these materials without anti-nutritional components. A very important role in breeding is played by the height of genotypes; the lower growth facilitates the process of mechanised harvesting. The Gene Bank of the CRI evaluated and selected potentially suitable genotypes for conditions in the Czech Republic. The plant material is mainly obtained from other world institutions, such as gene banks, universities, and botanical gardens, mainly from Europe, the USA, Australia, and countries in Asia. Several genotypes are obtained from private subjects. The plant material does not have characters of hybrids. All new accessions are tested over three successive years. Subsequently, original data are obtained showing suitability for applications of new plant materials in the conditions of the Czech Republic. These sorghum genotypes are described and stored in a gene bank under defined conditions as an important source of valuable genetic material for a potential breeding programme in the region of Central Europe.

Year	New cultivated genotypes	Not grown up genotypes	Not flowering genotypes	Not ripening genotypes	Total no. of sown genotypes
2010	59 (34.8%)	38 (22.3%)	7 (4.1%)	66 (38.8%)	170 (100%)
2011	58 (38.4%)	7 (4.6 %)	8 (5.3%)	78 (51.7%)	151 (100%)

Table 3. Summary of grain sorghum at the CRI, Prague Ruzyně.

The summary (**Table 3**) presents the losses of plant material caused by the evaluation under conditions of the Czech Republic. Every year around 30–40% of the genotypes were harvested. These genotypes have demonstrated their viability in the conditions of the Czech Republic. In 2014, a new variety of *Sorghum bicolor* 'Ruzrok' bred for conditions in the Czech Republic was registered (**Appendix III**). Considerable interest of breeders (abroad) is enjoyed by sorghum hybrids with Sudan grass (*Sorghum bicolor* x *Sorghum sudanense*) where there might be considerable variability between varieties. In the conditions of the Czech Republic, this is probably the most common form that is usually used for the production of high-quality silage, haylage with high hemicellulose content, direct feeding, grazing cattle, and biogas production. The aim of intensive breeding in both sorghum species suitable for silage production is BMR form (brown midrib)—the form of cytoplasmic mutation (CMS). These varieties possess higher digestibility where the outward characteristic is brown midrib.

5. Uses of foxtail millet and sorghum

Foxtail millet is a multipurpose crop. It is suitable for human consumption (grain) and livestock nutrition (grain, forage). For human consumption, the grain must be dehulled in the mills because the kernel and palea knit together. Published studies reported higher nutritional value than rice [50]. Tables 4–9 show the evaluation of three foxtail millet genotypes in 2002–2003 cultivated in the conditions of the Czech Republic (CRI, Prague Ruzyně). The numbers are the average values from two successive years. The content of crude proteins (11.42%) was higher than in rice, wheat, or corn. The ratio of pure protein is up to 91.5% [51, 52]. From protein fractions, the albumins and globulins represented 13.1%, prolamins 39.4%, glutelins 9.9%. According to the gluten content, foxtail millet's grains are considered for a gluten-free diet [52]. The content and composition of amino acids is beneficial for human health, as most of the cereals have low lysine content [53]. The content of essential amino acids (threonine, valine, methionine, isoleucine, leucine, and phenylalanine) presented in foxtail millet grains is about 41% higher than rice, 65% higher than in wheat flour, and approximately 51.1% more than in corn. These amino acids are important for poultry nutrition. As stated by Pack et al. [54], lysine, methionine, threonine, and cysteine are essential for nutrition and affordable cost for the preparation of animal feed. This crop can contribute to a natural increase of these substances in animal feed. The observed content of fat ranged from 5.02 to 5.56%; similar results were published by Zhang et al. [55], which is more than it is known in wheat and maize. There is a higher content of unsaturated fatty acids (namely linoleic, linolenic, and gadoleic) compared with fatty acids of maize [56]. Carbohydrate content is 72.8% and it is lower than in rice, wheat, and maize. The size of starch granules ranges from 0.8 to 9.6 μm. The content of amylose and amylopectin depends on the variety. There are so-called waxy varieties with high content of amylopectin or with low or high content of amylose [57]. Zhu [58] observed millet as a starch supplying crop that appeared strategically promising. The content of minerals iron, zinc, copper, and magnesium is higher in comparison with rice and wheat. The observed content of vitamins was consistent with published results of Saleh et al. [59], whereas the content of

Ca is considered on a similar level as in rice and wheat. Seeds of foxtail millet are rich in Se and the fibre content (11%) is four times higher than that of rice.

		Dry matter	Ash	Fat	Protein	Fibre
Year	2002	93.83 ± 2.08a	3.23 ± 0.22a	5.20 ± 0.21a	12.67 ± 0.32a	18.83 ± 0.42a
	2003	93.27 ± 0.10a	2.96 ± 0.10a	5.30 ± 0.43a	12.07 ± 0.08a	15.91 ± 1.81a
Genotype	01Z230023	92.33 ± 1.17a	2.99 ± 0.01a	5.15 ± 0.13a	12.48 ± 0.46a	17.09 ± 2.28a
	01Z230002	94.41 ± 1.54a	3.19 ± 0.23a	5.56 ± 0.29a	12.45 ± 0.64a	18.60 ± 1.00a
	01Z230014	93.92 ± 0.82a	3.11 ± 0.36a	5.02 ± 0.06a	12.18 ± 0.18a	16.43 ± 2.93a

Table 4. Basic nutritional components (g 100 g^{-1} of sample) of foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

		B1	B2	Niacin	Pantothenic acid	B6	Carotenoids
Year	2002	0.40 ± 0.01a	0.10 ± 0.01a	2.73 ± 0.06a	1.31 ± 0.19a	0.30 ± 0.03b	0.67 ± 0.08a
	2003	0.39 ± 0.04a	0.12 ± 0.00a	3.23 ± 0.15b	1.13 ± 0.10a	0.24 ± 0.02a	0.73 ± 0.06a
Genotype	01Z230023	0.39 ± 0.04a	0.10 ± 0.02a	2.95 ± 0.35a	1.13 ± 0.13a	0.25 ± 0.03a	0.78 ± 0.04b
	01Z230002	0.41 ± 0.03a	0.11 ± 0.01a	3.10 ± 0.42a	1.34 ± 0.28a	0.28 ± 0.06a	0.70 ± 0.03ab
	01Z230014	0.38 ± 0.01a	0.11 ± 0.02a	2.90 ± 0.28a	1.21 ± 0.02a	0.29 ± 0.04a	0.64 ± 0.06a

Table 5. Vitamin content (mg 100 g^{-1} of sample) in foxtail millet (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

In comparison with other cereals (wheat and maize), the foxtail millet grains reached higher values of some evaluated nutritional components. According to Zhang and Liu [60], foxtail millet demonstrated remarkable peroxyl radical scavenging capacity and cellular antioxidative activity due to its content of phenolic compounds, phenolic acids, and carotenoids, and it is considered as a valuable cereal with potential in the prevention and management of cardiovascular and geriatric diseases, as well as cancers. Foxtail millet is considered as an ideal crop for producing food for diabetics.

		Aspartic acid	Threonine	Serine	Glutamic	Proline	Glycin
Year	2002	0.76 ± 0.07a	0.39 ± 0.02a	0.47 ± 0.03a	1.94 ± 0.12a	1.07 ± 0.15a	0.27 ± 0.03a
	2003	0.80 ± 0.01a	0.45 ± 0.02b	0.45 ± 0.03a	2.07 ± 0.05a	0.87 ± 0.17a	0.30 ± 0.01a
Genotype	01Z230023	0.75 ± 0.09a	0.40 ± 0.04a	0.46 ± 0.04a	1.96 ± 0.22a	0.99 ± 0.11a	0.26 ± 0.03a
	01Z230002	0.79 ± 0.00a	0.44 ± 0.05a	0.46 ± 0.04a	2.06 ± 0.04a	0.93 ± 0.27a	0.29 ± 0.03a
	01Z230014	0.81 ± 0.01a	0.42 ± 0.03a	0.46 ± 0.03a	2.00 ± 0.02a	1.00 ± 0.27a	0.30 ± 0.00a

Table 6. Amino acid content (g 100 g^{-1} of sample) in foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

		Alanine	Valine	Methionine	Isoleucine	Leucine	Tyrosine	Phenyl-alanine
Year	2002	0.94 ± 0.08a	0.50 ± 0.02a	0.29 ± 0.04a	0.50 ± 0.10a	1.53 ± 0.15a	0.37 ± 0.05a	0.64 ± 0.05a
	2003	0.95 ± 0.03a	0.54 ± 0.03a	0.18 ± 0.06a	0.54 ± 0.10a	1.31 ± 0.10a	0.30 ± 0.02a	0.78 ± 0.03b
Genotype	01Z230023	0.92 ± 0.09a	0.51 ± 0.04a	0.22 ± 0.04a	0.53 ± 0.16a	1.32 ± 0.05a	0.32 ± 0.02a	0.67 ± 0.12a
	01Z230002	0.97 ± 0.01a	0.54 ± 0.05a	0.22 ± 0.15a	0.52 ± 0.12a	1.42 ± 0.28a	0.33 ± 0.02a	0.72 ± 0.07a
	01Z230014	0.96 ± 0.05a	0.51 ± 0.00a	0.27 ± 0.05a	0.51 ± 0.04a	1.52 ± 0.14a	0.36 ± 0.11a	0.74 ± 0.11a

Table 6. (continues).

		Histidine	Lysine	Arginine	Cysteine	Total
Year	2002	0.28 ± 0.02a	0.18 ± 0.02a	0.38 ± 0.03a	0.22 ± 0.00a	10.75 ± 0.90a
	2003	0.26 ± 0.09a	0.23 ± 0.01a	0.59 ± 0.02b	0.24 ± 0.04a	10.86 ± 0.47a
Genotype	01Z230023	0.31 ± 0.08a	0.19 ± 0.05a	0.48 ± 0.19a	0.24 ± 0.02a	10.53 ± 1.17a
	01Z230002	0.25 ± 0.06a	0.21 ± 0.03a	0.48 ± 0.14a	0.21 ± 0.02a	10.84 ± 0.58a
	01Z230014	0.24 ± 0.05a	0.21 ± 0.01a	0.49 ± 0.11a	0.24 ± 0.03a	11.04 ± 0.35a

Table 6. (continues).

		Myristic (14:0)	Palmitic (16:0)	Palmitooleic (16:1)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)
Year	2002	0.13 ± 0.03b	7.99 ± 0.80a	0.13 ± 0.02a	1.26 ± 0.15a	16.31 ± 2.00a	69.77 ± 1.50a
	2003	0.09 ± 0.02a	9.47 ± 0.98a	0.14 ± 0.02a	1.40 ± 0.08a	15.59 ± 1.34a	69.67 ± 0.19a
Genotype	01Z230023	0.13 ± 0.04a	8.85 ± 2.21a	0.14 ± 0.01a	1.39 ± 0.06a	16.70 ± 2.70a	68.89 ± 1.12a
	01Z230002	0.09 ± 0.02a	8.14 ± 0.45a	0.15 ± 0.02a	1.33 ± 0.23a	16.25 ± 1.26a	70.23 ± 1.06a
	01Z230014	0.11 ± 0.03a	9.21 ± 0.49a	0.12 ± 0.00a	1.27 ± 0.13a	14.91 ± 0.08a	70.06 ± 0.28a

Table 7. Fatty acid content (g 100 g^{-1} of fatty acid) in the oil of foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

		Linolenic (18:3)	Arachic (20:0)	Gadoleic (20:1)	Behenic (22:0)
Year	2002	3.04 ± 0.46a	0.46 ± 0.03a	0.39 ± 0.02a	0.36 ± 0.05a
	2003	2.59 ± 0.27a	0.41 ± 0.05a	0.36 ± 0.13a	0.24 ± 0.03a
Genotype	01Z230023	2.58 ± 0.09a	0.43 ± 0.09a	0.35 ± 0.06a	0.32 ± 0.13a
	01Z230002	2.81 ± 0.72a	0.43 ± 0.01a	0.32 ± 0.07a	0.27 ± 0.07a
	01Z230014	3.06 ± 0.33a	0.46 ± 0.01a	0.46 ± 0.07a	0.31 ± 0.05a

Table 7. (continues).

		Na	K	Ca	Mg	P
Year	2002	2.73 ± 0.85a	401.33 ± 29.54a	18.07 ± 1.40a	127.00 ± 3.46a	353.33 ± 10.02a
	2003	3.37 ± 0.85a	364.00 ± 7.21a	18.27 ± 1.66a	124.33 ± 5.86a	359.00 ± 16.82a
Genotype	01Z230023	3.95 ± 0.35b	368.50 ± 3.54a	17.50 ± 1.41a	125.50 ± 4.95a	364.50 ± 10.61a
	01Z230002	2.90 ± 0.71ab	379.50 ± 33.23a	17.85 ± 1.91a	127.00 ± 5.66a	353.50 ± 16.26a
	01Z230014	2.30 ± 0.28a	400.00 ± 42.43a	19.15 ± 0.92a	124.50 ± 6.36a	350.50 ± 14.85a

Table 8. Content of mineral components (mg 100 g^{-1} of sample) in foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

		Zn	Fe	Cu	Mn
Year	2002	3.80 ± 0.10a	6.73 ± 1.86a	0.54 ± 0.04a	1.37 ± 0.15a
	2003	4.10 ± 0.10b	3.30 ± 0.26a	0.63 ± 0.09a	1.30 ± 0.17a
Genotype	01Z230023	3.90 ± 0.28a	4.65 ± 2.19a	0.55 ± 0.06a	1.30 ± 0.14a
	01Z230002	4.05 ± 0.21a	6.00 ± 3.96a	0.66 ± 0.11a	1.50 ± 0.00a
	01Z230014	3.90 ± 0.14a	4.40 ± 1.13a	0.55 ± 0.02a	1.20 ± 0.00a

Table 8. (continues).

Foxtail millet can also be used as an animal feed. Tables 9 and 10 show basic nutritional composition and amino acid composition of foxtail green biomass. The straw is ideal for cattle because of its high nutritional value (the protein content of 6.0%, 26.0% simple sugars; xylogen 24.2%; 42.2% fibrin), which is much higher than in many other crops. Moreover, foxtail millet straw is relatively soft and easily digestible for cattle [51].

ECN	Dry matter (%)	Ash (%)	Organic matter (%)	Fibre (%)	N × 6.25	N × 5.93	Fat (%)	Nitrogen-free substances (%)
01Z2300003	100	2.95	97.05	9.97	14.3	13.31	4.25	68.8
01Z2300009	100	2.23	97.77	8.7	16.66	15.8	4.2	68.21
01Z2300010	100	3.38	96.62	8.95	15.76	14.96	4.49	67.41

Table 9. Basic nutritional components in green biomass of foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

	g kg^{-1} of original value														
ECN	asp	thr	ser	glu	pro	gly	ala	val	ile	leu	tyr	phe	his	lys	arg
01Z2300003	2.1	0.79	1.4	5.2	2.42	0.73	2.49	1.32	1.14	3.92	0.68	1.42	0.83	0.58	0.88
01Z2300009	2.63	4.7	1.39	6.15	3.5	0.93	3.6	1.4	1.44	4.79	0.89	1.81	1.4	0.72	1.27
01Z2300010	1.71	0.65	0.99	4.57	2.23	0.69	2.16	1.41	1.2	3.37	0.66	1.26	0.75	0.48	0.66

Table 10. Amino acid content in green biomass of foxtail millet grains (data evaluated in the Gene Bank, CRI, Prague Ruzyně).

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Possibilities for sorghum utilisation are very broad. In the food industry, it is used for the production of sorghum sugar syrups, sweets, ethanol, alcoholic beverages, and beer because of easy and quick fermentation. The preparation of purée from flour and groats in combination with meat and vegetables is widespread [61]. Industrial use of sorghum flour is for the production of adhesives, oils, and starch [62]. Recently, a high increase in the production of ethanol as a fuel from biomass was recorded [63]. Sorghum is also suitable as a high-quality forage crop because of its high sugar content, very good digestibility, and high yields of green silage. Manifold technical sorghum is the raw material for the production of brushes and brooms.

Variety	Content of crude protein	Fat	BNLV	Fibre	Ash
Grain	12.8	3.3	76	5.9	2
Sugar	14.2	3.7	73.6	6	2.6
Technical	13.7	3.6	73	7.5	2.2

Table 11. Chemical composition of sorghum grains (%) from the collection of genetic resources in the Gene Bank, CRI Prague Ruzyně (2011).

The content of nutritional components differs depending on the cultivation site and conditions. **Table 11** shows original data as a result of chemical composition analysis of cultivated sorghum varieties in the Gene Bank (CRI, Prague Ruzyně). The content of starch is similar to maize at around 70%, protein content 8–16%, fat content 3.3%, minerals 1.9%, and crude fibre 1.9% [64]. As is commonly known, the content of proteins is strongly affected by nitrogen fertilisation; it elevates the content of prolamin fraction, which is known as karirin in the case of sorghum. This fraction is poor in lysine, arginine, histidin, and tryptophan and rich in prolin and glutamin. Rajki-Siklósi [49] presented a protein content in sorghum seeds from 10.0 to 10.7%. The tannin (proanthocyanidin) content together with some of the others is considered as a negative component, which negatively influenced digestibility. The amino acid composition of sorghum seeds is variable, according to published studies [65–67], depending on genotypes and cultivation localities. Lysine in commonly available genotypes covers almost 40% of the recommended dose of this essential amino acid, especially for children in developing countries. High lysine genotypes have higher content of lysine and the total content of amino acids is nutritionally more beneficial [68]. Interest in the cultivation of sorghum in Central Europe is growing with respect to climate change, utilisation for feeding purposes, and in human nutrition for the possibility of its use in gluten-free diets. There are genotypic differences when grain sorghum varieties compared to sugar sorghum show a favourable composition of protein fractions, a higher proportion of nutritionally valuable albumin and globulins, and a lower content of prolamins. Results of Petr et al. [52] confirmed the suitability of sorghum for a gluten-free diet.

Among the biologically active substances in sorghum is the prized content of phenolic acids, which are represented as protocatechuic acid, hydroxybenzoic, vanillic, caffeic, ferulic, and cinnamon. These acids are important for their high antioxidant properties. From the minerals in sorghum, there are interesting contents of phosphorus, magnesium, iron, zinc, copper, manganese, molybdenum, and chromium. Sorghum further comprises vitamins B1, B6, beta carotene, folacin, and pantothenic acid, which is important for metabolic processing of nutrients and irreplaceable for hormone synthesis [69]. The possibility of higher use for food purposes exist in Europe, which is at a low level at the moment.

In the Czech Republic, varieties and hybrids of sorghum are primarily used for feed and biogas production [70]. Traditional varieties of sorghum are now being replaced by new hybrids with favourable agrotechnical and nutritional properties. In recent years, the hybrids most used for these purposes are derived from crosses of grain or sugar sorghum with Sudan grass. Their advantage is the high-quality production of green matter. Intensive breeding has managed to dismantle the previously high content of alkaloid durin and increase the digestibility of organic nutrients.

In 2009 and 2010, field experiments with selected sorghum materials were carried out at the Gene Bank (CRI, Prague Ruzyně). The size of the field was 4.5 m^2 in three repetitions. The plant materials used were commercial varieties of sorghum provided by the companies Seed Service, Saatbau Linz, and Syngenta. Some of the tested materials were obtained from the Gene Bank (CRI, Prague Ruzyně). The results of the experiments are summarised in Tables 12 and 13.

Variety	**Height**	**Biomass**	**Content of essential nutrition in % dry matter (d.m.)**				
	(cm)	**(kg m $^{-2}$)**	**N**	**P**	**K**	**Ca**	**Mg**
Čirok	200.53 ± 27.43	7.69 ± 2.46	1.86 ± 0.42	0.25 ± 0.07	3.25 ± 1.13	0.71 ± 0.11	0.24 ± 0.04
Goliath [1]	228.67 ± 22.27	10.10 ± 0.93	1.82 ± 0.40	0.25 ± 0.08	3.41 ± 1.24	0.70 ± 0.09	0.25 ± 0.02
Sucrosorgo 506 [2]	209.50 ± 24.34	8.62 ± 2.16	1.87 ± 0.29	0.26 ± 0.07	3.40 ± 0.97	0.69 ± 0.12	0.24 ± 0.03
Nutri Honey [3]	199.33 ± 20.85	7.18 ± 1.37	1.75 ± 0.37	0.23 ± 0.05	2.58 ± 0.71	0.65 ± 0.11	0.23 ± 0.03
Latte [4]	197.67 ± 25.01	7.96 ± 3.60	1.70 ± 0.55	0.25 ± 0.06	2.92 ± 1.09	0.63 ± 0.09	0.22 ± 0.04
Honey Graze BMR [5]	194.83 ± 14.80	5.60 ± 1.46	1.83 ± 0.53	0.23 ± 0.08	3.52 ± 1.79	0.76 ± 0.05	0.24 ± 0.04
Big Kahuna BMR [6]	173.17 ± 30.04	6.71 ± 2.25	2.17 ± 0.37	0.29 ± 0.08	3.66 ± 0.73	0.82 ± 0.06	0.28 ± 0.02

1. Goliath—early hybrid, suitable for biogas production.
2. Sucrosorgo 506—hybrid, high yields of green biomass even in places not suitable for corn silage.
3. Nutri Honey—hybrid of sorghum and Sudan grass, suitable for forage and grazing.
4. Latte—forage variety, high resistance to drought.
5. Honey Graze BMR—hybrid suitable for making silage, hay, green feed or grazing; a lower lignin content.
6. Big Kahuna BMR—hybrid for silage, photosensitive to short-day.

Table 12. Evaluated parameters of biomass in sorghum varieties; mean values from 2009 to 2010.

Variety	Height	Biomass	Content of essential nutrients in % dry matter (d.m.)				
	(cm)	(kg m^{-2})	N	P	K	Ca	Mg
K—81	291.00 ± 4.58a	26.08 ± 1.97a	1.00 ± 0.04abc	0.15 ± 0.01ab	1.03 ± 0.06abc	0.47 ± 0.01c	0.21 ± 0.01a
Kecskemeti	314.67 ± 4.51a	26.24 ± 5.84a	0.97 ± 0.10bc	0.15 ± 0.01ab	0.86 ± 0.07b	0.45 ± 0.02bc	0.22 ± 0.02a
SO—29	302.33 ± 7.02a	26.61 ± 2.74a	1.16 ± 0.10abc	0.19 ± 0.02a	1.08 ± 0.05a	0.36 ± 0.02a	0.17 ± 0.00a
GK 4 Zsofia	308.67 ± 7.57a	24.07 ± 4.41a	1.22 ± 0.09ab	0.18 ± 0.02ab	0.89 ± 0.03bc	0.43 ± 0.02abc	0.20 ± 0.02a
6—without tannin (sugar)	304.00 ± 19.70a	20.04 ± 3.39a	1.26 ± 0.12a	0.18 ± 0.04ab	1.09 ± 0.07a	0.40 ± 0.03abc	0.19 ± 0.03a
21/00	308.00 ± 14.00a	29.51 ± 7.21a	1.25 ± 0.15ab	0.20 ± 0.04a	0.89 ± 0.12bc	0.39 ± 0.04ab	0.19 ± 0.03a
56/01	317.00 ± 7.00a	28.25 ± 4.51a	1.17 ± 0.08abc	0.17 ± 0.01ab	1.04 ± 0.15ac	0.43 ± 0.05abc	0.18 ± 0.03a
GK 5 Zsofia	294.67 ± 12.66a	20.25 ± 1.83a	1.27 ± 0.06a	0.18 ± 0.01ab	1.10 ± 0.08a	0.39 ± 0.04ab	0.19 ± 0.01a
Latte	312.67 ± 9.07a	28.51 ± 3.51a	0.89 ± 0.05c	0.12 ± 0.00b	1.16 ± 0.09a	0.37 ± 0.02a	0.18 ± 0.01a

Values with different letter indexes were statistically significantly different $P \leq 0.05$.

Table 13. Evaluated parameters of biomass in sorghum varieties; mean values from 2009–2010.

When the green biomass is mowed from the beginning of flowering, the protein content of the forage is very high, comparable with the content of the other young grasses or alfalfa. In that growth phase, the plants have a high content of soluble fibre, which decreases progressively with aging of the plants and the protein content is diluted as well. Significant lignification occurs after flowering of the plants.

Sorghums generally ensure high yields of biomass in appropriate conditions. The harvest depends on the purposes of cultivation. Achieved yields of sorghum biomass in field experiments performed by the CRI and analysis of other outcome measures are summarised in Tables 14 and 15.

Locality/variety	Sudanense grass	Hyso*	Grain sorghum	Sugar sorghum
Ruzyně	9.4	11.9	12.4	8.7
Troubsko	26.7	27.2	31.2	9.3
Lukavec	–	–	21.9	3.3
Chomutov	–	12.8	5.3	7.4
Mean	18.0	17.3	17.7	7.2

*variety hybrid between Sudanense grass and technical sorghum

Table 14. Average yields of biomass dry matter (t. ha^{-1}) in tested sorghum genotypes in the period 1993–2004.

The experiments obtained average yields of dry matter of biomass from 27.06 t ha^{-1} in Troubsko to 5.14 t ha^{-1} in Lukavec. In Lukavec, there were not suitable conditions for tested sorghum hybrids. Without consideration of these results, the average yield of dry matter of biomass in all genotypes was 15.56 t ha^{-1} (data not shown). The presented average yield of dry matter of biomass was influenced by values obtained from sugar sorghum genotypes, which were low in all the tested localities (**Table 14**). From the tested sorghum genotypes all reached similar yields on average (18.02 t ha^{-1} Sudan grass, 17.71 t ha^{-1} grain sorghum and 17.29 t ha^{-1} "Hyso"). In the comparison of localities, the highest yields of biomass were gained in all tested genotypes in the warmest locality in Troubsko and, in contrast, the lowest yields were obtained in Lukavec, the coldest locality. Sorghum positively reacted to graded doses of nitrogen fertilisation. In our tests, the yield of biomass was increased by around 13.3% in experimental plots fertilised with 60 kg ha^{-1} of N and around 17.0% in plots fertilised with 120 kg ha^{-1} of N in comparison with un-fertilised plots. Similarly, experiments in Germany confirmed high yields of sorghum from 15 to 20 t ha^{-1} in warm localities with a sum of temperatures higher than 2000°C. Also, the sowing rate had a significant effect on biomass yield (data not shown). In all localities, higher yield was obtained by the application of a sowing rate of 60 seeds per m^2.

The influence of locality and nitrogen fertilisation on yields on above ground biomass was evaluated. The effect of the harvest time on water content in the harvested plant material, the loss of biomass over the winter period, the content of essential nutrients and energy content in plants were all observed. Also, the comparison of the monitored genotypes (varieties) of sorghum in terms of suitability for burning and the impact of the date of harvest on yield, water content, mineral content, and content in biomass were evaluated.

From the point of view of energy utilisation and storage of biomass, the content of the dry matter is important at harvest time. In an autumn harvest, the water content is high (around 66%). By postponing the harvest to spring time, the water content in plants is reduced but, due to plant morphology and high weight of panicles, lodging occurs resulting in losses of biomass.

The content of minerals in plants is one of the most important factors for the determination of nutrient uptake by yields, in terms of combustion of the biomass, the formation of biogas, etc. Generally, it can be said that the content of nitrogen in plants decreases with the age of the plants and the harvest time. In general, delaying harvest time also reduces the content of the monitored elements in the biomass.

In Europe (notably Germany, Austria, and Italy) where bioenergy is focused on biogas rather than ethanol, sorghum has recently drawn attention as a novel bioenergy crop. Maize is currently used in the Czech Republic for producing biogas. With respect to conserving and increasing the biodiversity of cultivated agriculture crops and eliminating the negative effects on the environment of monoculture cultivation of maize, the alternative crops are sought-after. Sorghum should be one suitable possibility. Sorghum is considered as a dry tolerant crop suitable for cultivation on light soils and arid areas [71]. Habyarinama et al. [72] proposed the development of drought tolerant sorghum hybrids in order to increase and stabilise biomass production in the Mediterranean region. Recently, Windpassinger et al. [73] stated that sorghum provided high yields of biomass suitable for silage production under temperate conditions. The interest in sorghum cultivation may increase in the future due to changing climate conditions in Central Europe.

Our experimental data of chemical composition and fermentations processes of the broad sorghum collection corresponded to [74–76]. The results obtained showed high variability in the chemical composition, and biogas production in different varieties and hybrids. This fact highlighted the importance of careful selection of suitable varieties and genotypes based on testing the sorghum collection at the Gene Bank of the CRI, Prague Ruzyně. **Table 15** presents comparative data of the evaluated sorghum and maize. Sorghums contained a high content of ash (approx. 50%), fibre (approx. 60%), lignin (approx. 30%), and a low content of protein (approx. 8%) and fat (approx. 30%). This is the reason for lower yields of methane and biogas from sorghum (mainly from hybrids) in comparison with maize (6–16%). However, from 1 ha of sorghum, it is possible to obtain a similar or even higher amount of biogas (mainly methane) thanks to the higher yields of dry matter of biomass. For these purposes, the selection of suitable genotypes is essential with the emphasis on early maturation for conditions in the Czech Republic.

Parameter	Sorghum	Maize
Ash (% in d.m.)	6–12	4–8
Crude protein (% in d.m.)	5–9	6–9
Carbohydrates total (% in d.m.)	8–18	8–18
Crude fat (% in d.m.)	1–3	2–4
Crude fibre (% in d.m.)	32–44	20–28
Neutral detergent fibre (NDF) (% in d.m.)	48–62	32–44
Hemicelluloses (% in d.m.)	12–18	12–16
Lignin (% in d.m.)	3–6	2–5
Losses of dry matter in silage (% in d.m.)	2–8	2–6
Yield of biogas ($Nm^3.t^{-1}$ of d.m.)	420–620	400–710
Methane concentration (%)	52–55	52–55
Methane yield (Nm^3 t^{-1} in d.m.)	220–340	210–390
Methane yield (Nm^3 t^{-1} of org. d m.)	240–380	230–440
Average yields of dry matter of biomass (t ha^{-1})	9–22	8–18
Methane yields (Nm^3 ha^{-1})	2000–7500	1700–7000

Table 15. Mean values of sorghum biomass composition, biogas, and biomass in comparison with maize.

Field experiments in four localities (Ruzyně, Lukavec, Chomutov, and Troubsko) in the years from 1993 to 2004 with selected sorghum genotypes (Sudan grass, "Hyso," grain sorghum, and sugar sorghum) considered for potential energy are shown in **Table 16**; they were conducted under three different nitrogen doses (0, 60, 120 kg ha^{-1}) and one or two levels of seed rates (40 and 60 germinating seeds per 1 m^2) by spacing 25 cm and two harvests period in the autumn and spring.

Locality/variant	Ruzyně	Troubsko	Lukavec	Chomutov	Mean
Average N0	10.5	26.1	2.3	10.0	12.2
Average N1	11.7	27.2	6.1	11.5	14.1
Average N2	12.2	27.9	7.0	11.8	14.7
Average V1	10.9	27.0	4.4	12.2	13.6
Average V2	12.0	27.2	5.9	10.1	13.8
Mean	11.5	27.1	5.1	11.1	13.7

Notes: Mineral nitrogen fertilization: N0 = 0, N1 = 60, N2 = 120 kg ha^1.
Supposed no. of plants per m^2: V1 = 40, V2 = 60.

Table 16. Average yields of dry matter of biomass (t ha^{-1}) according to variants in experimental fields in the period 1993–2004.

6. Conclusion

Foxtail millet has a long history of cultivation around the world and is valued for its nutritional content and health promoting properties, its ability to grow under low-input conditions, and its tolerance to extreme environmental stresses. Similarly, sorghum has recently attracted attention as a novel bioenergy crop. In a world facing limited natural resources and climate change, we considered both mentioned species as having great potential for food use in the case of foxtail millet and for biomass production in case of sorghum in arid and semi-arid areas of the Czech Republic and further for other areas of Central European countries. Genetic resources of both species can provide genotypic and phenotypic variability for conservation and exploitation of biodiversity in the context of warmer weather affecting global agricultural production.

Appendix I. New variety of *Setaria italica* ′Ruberit′ bred for conditions of the Central Europe.

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Appendix II. New genotype of *Setaria italica* ´Rucereus´ bred for conditions of the Central Europe.

Appendix III. New variety of *Sorghum bicolor* ´Ruzrok´ bred for conditions of the Central Europe.

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