Research on High-efficiency Seed Production Technology for Water-saving and Drought-resistant Hybrid Millet Variety Zhangzagu 19

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Abstract [**Objectives**] This study was conducted to improve the seed production efficiency of water-saving and drought-resistant hybrid millet in production. [**Methods**] A high-efficiency seed production technology for water-saving and drought-resistant hybrid millet varieties was developed by integrating aspects such as parental line sources, botanical characteristics, biological traits, seed production yield structure, key technical points of seed production, and suitable planting regions. [**Results**] Under standardized pre-sowing preparation and field management, both parents are simultaneously sown around May 20 with a planting row ratio of 2∶6 (female∶male), a row spacing of 20 cm and plant spacing of 10 cm for the female parent, and a row spacing of 35 cm and plant spacing of 15 cm for the male parent. Both parents are fertilized simultaneously with 375 kg/hm^2 of urea at the booting stage combined with intertillage or rainfall, and 225 kg/hm^2 of urea at the grain-filling stage combined with irrigation. Strict hybrid removal, proper pollination and timely harvesting can significantly increase the yield of seed production. [**Conclusions**] This technology can be fully applied to large-scale seed production of water-saving and drought-resistant hybrid millet, providing seed supply support for cultivation in arid and semi-arid regions. It helps alleviate issues such as excessive groundwater extraction and water scarcity while enhancing planting efficiency, increasing yield, and boosting increase of farmers' income.

Key words Water saving; Drought resistance; Hybrid millet; Seed production; Zhangzagu 19

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China has a vast territory with significant environmental variations among different regions, and is characterized by substantial annual fluctuations and uneven distribution of water resources, leading to varying degrees of water scarcity in both the northern and southern areas[1]. In most northern regions, the primary issue is resource-based water shortage, while seasonal water scarcity dominates in the semi-humid areas of the south. With the intensification of global climate change, regional water shortage is expected to worsen. Thus, water scarcity is not a localized problem but has become a major factor hindering agricultural production and national economic development[2]. How to feed 25% of the world's population with only 7.2% of its arable land, how to increase crop yield, how to resolve the imbalance between water supply and demand in agricultural production and how to achieve higher yield while conserving resources have become major challenges in the field of agriculture[3]. Promoting water-saving crop varieties and their supporting seed production techniques is not only imperative but also a proven effective solution[4].

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Zhangzagu 19, a high-efficiency, water-saving and drought-resistant hybrid millet variety, was developed by Institute of Foxtail Millet Research, Zhangjiakou Academy of Agricultural Sciences. With only one pre-sowing irrigation (1 200 m^3/hm^2), it can achieve a yield of over 5 000 kg/hm^2[5]. Well-suited for arid and semi-arid regions with annual rainfall of 250 – 400 mm, it stands out as an exemplary water-saving grain crop variety. In this study, the standardized seed production technology of water-saving and drought-resistant hybrid millet Zhangzagu 19 was summarized, aiming to provide technical guidance for its standardized breeding and large-scale production. This study seeks to accelerate the demonstration and promotion of water-saving hybrid millet varieties, helping to alleviate agricultural water scarcity challenges[6] and actively supporting environmentally friendly and water-efficient initiatives.

Origin and Characteristics of Parental Lines and Hybrid

Parental lines for seed production

Female parent The female parent is male sterile line A2, developed by crossing the photo-thermo-sensitive male sterile source "821" from Zhangjiakou Academy of Agricultural Sciences with 1066A. Its fertility is controlled by light and temperature conditions, exhibiting stable conversion. Characteristics: The seedlings are yellow, and turn light green after jointing. The stem height is 75.5 cm, and the plant is short, which is convenient for pollination in seed production fields. This variety obtained plant variety rights authorization in March 2014.

Male parent The male parent is the germplasm resource DH2. In the summer of 2007, "Longgu 14", a widely adaptable and drought-resistant variety developed by Gansu Academy of Agricultural Sciences, was crossed with the herbicide-resistant millet variety Ji 1 He to produce the F_0 generation. From the winter of 2007 to the winter of 2009, backcrossing was performed for four consecutive times, followed by two generations of selfing in 2010, resulting in the homozygous herbicide-resistant "Improved Longgu 14". During 2011 – 2012, the F_3 generation derived from crossing "Improved Longgu 14" with "Jingu 21" (a high-quality millet variety developed by Shanxi Academy of Agricultural Sciences) was extensively propagated. From this population, stable lines were selected and backcrossed with "Jingu 21" for three generations, resulting in eight restorer lines characterized by high quality, drought resistance, wide adaptability, and sethoxydim resistance. Through drought resistance evaluation in Dunhuang in 2013, the second material demonstrated superior comprehensive traits, good combining ability, and high yield, and was subsequently named "DH2". After two consecutive generations of selfing in winter 2013, the agronomically-stable restorer line "DH2" was obtained[7-8].

Hybrid

Variety introduction In 2014, the herbicide-resistant hybrid combination "A2 × DH2" (named "Zhangzagu 19") was developed by test-crossing the restorer line "DH2" with the photoperiod-thermo-sensitive male sterile line A2. From 2015 to 2016, it participated in the national millet variety regional trials for the early-maturing group in the northwest region. The variety exhibits green seedlings and green leaf sheaths, and has a growth period of 116 d under the condition of spring sowing. The plants are 121.99 cm in height, with 3 – 6 tillers per plant. The panicles are 25.3 cm in length, displaying a club-shaped panicle type that is moderately dense. The single panicle weight is 25.20 g, and the grain weight per panicle is 18.27 g. The hulling yield is 72.5%, and the milled rice rate is 79.5%. The 1 000-grain weight is 3.01 g. The variety features yellow grains and yellow rice. It is resistant to the herbicide sethoxydim.

Key cultivation techniques Cultivation should be conducted in fields with medium to high fertility. During land preparation, 37 500 – 45 000 kg/hm^2 of farmyard manure and 225 kg/hm^2 of diammonium phosphate are applied as the base fertilizer. Sowing period: In warmer regions, seeds are sown in early to mid-May. In cooler regions, sowing is carried out from late April to early May. The seeding rate is 11.25 kg/hm^2. Plant density: Yellow seedlings are removed (or sethoxydim is applied at the three-leaf stage at a dosage of 1 500 ml/hm^2. It is recommended to use imported sethoxydim products manufactured in Japan), and green seedlings are retained. The recommended seedling density per hectare is generally between 90 000 and 180 000 plants. It is suggested to use a hill planter, with 3 – 5 plants per hill and 90 000 – 120 000 hills per hectare. For fertilization, urea should be applied at a rate of 450 kg/hm^2, with 10 kg applied during the jointing stage and 20 kg applied before the heading stage. Pest and disease control: After seedling emergence, insecticides should be sprayed to control pests such as millet stem borer (*Chilo infuscatellus*) and *Oulema tristis*. Throughout the growth period, measures should be taken to prevent diseases including millet blast, foxtail millet rust, millet smut, and downy mildew. This variety exhibits excellent high-yield and stress-resistant traits, and has wide adaptability across different regions. It is suitable for spring sowing in areas with an accumulated temperature ≥10 °C reaching 2 450 °C or above, such as Hebei, Shanxi, Shaanxi, Gansu, and Inner Mongolia.

High-efficiency Seed Production Technology

Pre-sowing preparation

Field selection Flat open fertile sandy loam soil with good drainage and irrigation is selected. Continuous cropping should be avoided. The best previous crop is legumes.

Land preparation During autumn tillage, deep plowing (20 – 25 cm depth) is conducted after harvesting the preceding crop. Before spring sowing, when the soil surface has thawed but the lower layer still contains ice, the topsoil should be loosened by harrowing with tines set to reach the frozen layer, and earlier harrowing leads to better results. The desired standard is to achieve a level field with loose topsoil and firm subsoil, free of large clods and significant crop residues or stubbles.

Base fertilizer Before sowing, sufficient base fertilizer is applied in combination with land preparation. Generally, 37 500 – 52 500 kg/hm^2 of decomposed farmyard manure and 375 kg/hm^2 of ternary compound fertilizer are applied.

Spring irrigation time Spring irrigation should be carried out 5 – 7 d before sowing.

Isolation zone Methods such as spatial isolation, phenological isolation, natural barriers, and tall crop isolation can be adopted. Spatial isolation: The distance between hybrid seed production fields and pollen sources of the same crop but different lines should be no less than 200 m. Phenological isolation: Staggered sowing dates or mulching can be adopted to completely separate the flowering periods of hybrid seed production fields and adjacent crops of different lines. Generally, it is advisable to stagger for 15 – 20 d. Natural barriers and tall crop isolation: Natural barriers such as mountains, villages or forests can be utilized for isolation. Alternatively, tall crops such as corn, sorghum or sunflower can be planted in a 50-meter-wide strip between hybrid seed production fields and adjacent fields of the same crop with different lines for isolation.

Sowing techniques

Sowing time Sowing time is a crucial agronomic cultivation technique that significantly regulates meteorological factors such as light, temperature, water, and air during the crop growth period. Sowing too early can lead to premature plant aging, reduced grain number per spanicle, and lower yield. Sowing too late results in a significant decrease in both grain number per spanicle and 1 000-grain weight, ultimately affecting millet yield formation. The seed

production of Zhangzagu 19 is conducted in Wanquan District, Huailai District, Economic Development Zone, and Huaian District of Zhangjiakou City, with synchronous sowing of parental lines. Based on the analysis of how different sowing dates affect seed production yield (Table 1), the optimal sowing period has been determined to be around May 20.

Table 1 Effects of different sowing dates on seed production of "Zhangzagu 19"

No.	Date for seeding	Average yield//kg/hm^2
1	May 10	1 518.3
2	May 20	2 000.6
3	June 1	1 793.4

Sowing method Hill-drop sowing is conducted with a sowing depth of 3 – 5 cm. Immediate compaction is performed after sowing.

Planting density Based on the impact of different parent plant spacing on seed production yield (Table 2), the optimal plant spacing for parental lines was determined. The results indicate an optimal parental line row ratio of 2 ∶ 6, remmmended spacing of 20 cm between rows and 10 cm between plants for the female parent, and remmmended spacing of 35 cm between rows and 15 cm between plants for the male parent.

Table 2 Effects of different parental plant spacing on the seed production yield of "Zhangzagu 19"

No.	Plant spacing of female parent//cm	Plant spacing of male parent//cm	Average yield//kg/hm^2
1	6	10	1 363.7
2	10	15	2 025.9
3	14	20	1 844.7

Pre-emergence management

After sowing, the soil is compacted promptly to ensure close contact between seeds and soil, preventing looseness on both top and bottom layers and facilitating rapid water absorption and germination. If heavy rain occurs between emergence and the stage of three leaves and one heart and causes mud to flow into the heart leaves, methods such as soil compaction should be promptly applied to aid seedling emergence and minimize loss.

Thinning and final singling

When the seedlings reach a height of 5 – 6 cm, thinning and final singling are carried out. Off-type plants are removed during thinning and final singling.

Topdressing and irrigation

Based on the analysis of the effects of different fertilization methods on seed production yield (Table 3), the optimal fertilization approach is to apply 375 kg/hm^2 of urea during the booting stage combined with cultivation or rainfall, and 225 kg/hm^2 of urea during the grain-filling stage combined with irrigation. Both the male and female parent plants should be fertilized simultaneously, avoiding excessive application.

Table 3 Effects of different topdressing methods on seed production

kg/hm^2

No.	Total application rate	Booting stage	Grain-filling stage	Average yield
1	300	150	150	1 399.5
2	450	300	150	1 705.1
3	600	375	225	1 983.0
4	750	375	375	1 729.9

Removal of off-type and inferior plants

(1) Removal at jointing stage: After jointing, off-type plants, inferior plants, diseased plants, and suspicious plants are identified and uprooted based on key traits such as plant height, leaf color, and tillering ability.

(2) Removal at flowering stage: Before flowering, off-type plants are promptly removed from both male and female parent rows based on key traits such as panicle shape, plant type, and glume color.

(3) Removal before harvest: Off-type plants are eliminated from the female parent rows prior to harvest.

(4) Removal during procurement: During seed procurement, male panicles mixed in the female parent, fully-filled female panicles and any other off-type panicles are removed.

Supplementary pollination

(1) Manual supplementary pollination: After the male parent begins flowering, manual supplementary pollination is performed every morning when there is no dew on the flag leaves of the female parent and a light flick of the male panicles releases a mist-like pollen cloud. The male panicles are gently shaken toward the female panicles until all pollen is dispersed. The pollination period typically lasts 10 to 15 d.

(2) Drone pollination: After the male parent starts flowering, supplementary pollination is conducted every morning when there is no dew on the flag leaves of the female parent and a light flick of the male panicles releases a mist-like pollen cloud. The drones fly at a height of 3 m above the male panicles at a speed of approximately 2.5 m/s, with the flight direction perpendicular to the planting rows. When a drone hovers in the air, it generates a maximum downward wind speed of 9.8 m/s. The downward wind force and swirling airflow produced by the rotor blades lift the pollen from the male parent and disperse it onto the stigma of the female parent, and each drone covers a width of 4 – 5 m each time. The pollination is performed 1 – 2 times daily. The following day, the drones switch their starting position between the first and the last plots in the field, and pollination is continued for 10 d consecutively.

Harvesting and threshing

The grains should be harvested at an optimal time. The male parent is removed before collecting the female parent. The female parent undergoes separate transportation, sun-drying, threshing, and storage processes.

Discussion

Foxtail millet, as a typical environmentally friendly crop,

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aphid damage. When aphid populations reach the control threshold (1 500 aphids per 100 plants or an infested plant rate of 50%), insecticides such as imidacloprid, acetamiprid, or thiamethoxam can be sprayed for control. Soybean pod borers damage soybean when their larvae bore into pods and feed on the seeds, creating "worm holes", which reduce both soybean quality and yield. This pest produces 4 to 6 generations per year, and overwinters as mature larvae in cocoons within the soil. Adults lie in the daytime and come out at night, and lay eggs on pods. After hatching, the larvae bore into the pods and cause damage. During the peak egg-hatching period and before the larvae bore into the pods, insecticides such as emamectin benzoate, chlorantraniliprole or deltamethrin can be selected and sparyed with a focus on thorough coverage of the bean pods.

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demonstrates excellent adaptability and high yield potential in most arid and marginal lands with poor soil fertility. The development of hybrid foxtail millet has further enhanced its high yield, superior quality, and stress-resistant characteristics. The research and application of high-efficiency seed production technology for water-saving and drought-resistant hybrid foxtail millet can provide ample seed reserves and support for such hybrids. This accelerates the promotion of foxtail millet cultivation in arid and semi-arid regions, effectively improves agricultural water-use efficiency, and increases its yield and farmers' and incomes, thereby contributing to ensuring food production security while advancing agricultural ecological civilization and green development principles[9].

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