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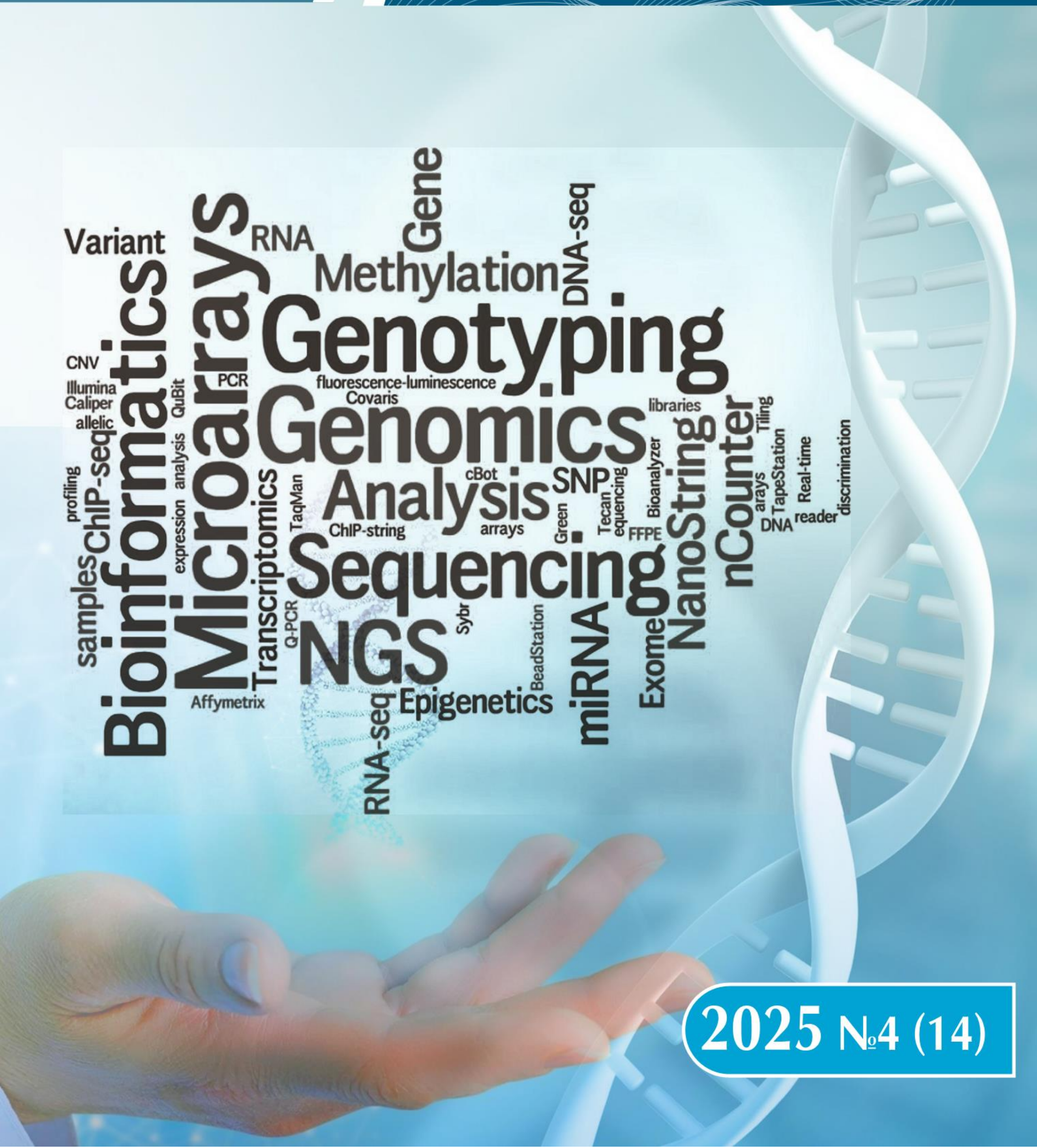

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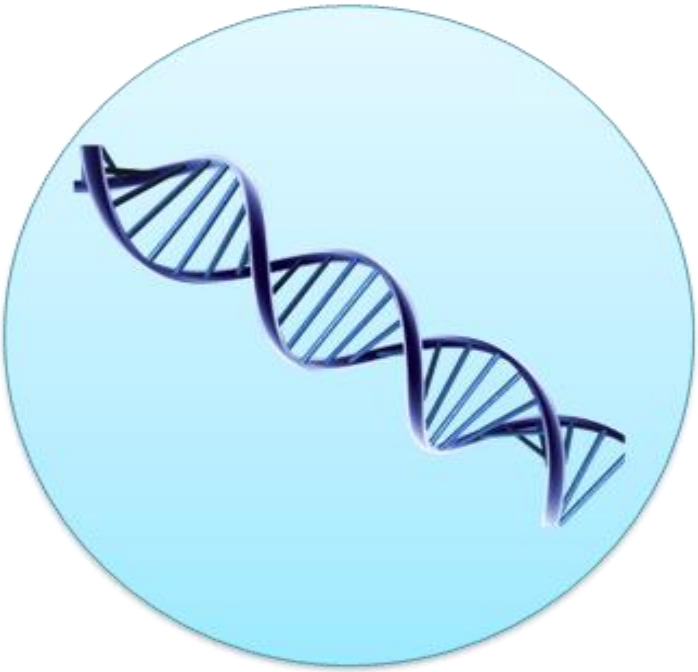

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PHYSIOLOGY OF SAFFLOWER (*CARTHAMUS TINCTORIUS* L.)

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Summary. Safflower (*Carthamus tinctorius* L.) is one of the drought-tolerant oilseed crops cultivated in saline and arid regions of Uzbekistan. This article presents an overview of the morphological structure of safflower, as well as its photosynthetic characteristics, water and mineral nutrient metabolism, hormonal regulation, stress tolerance, and molecular-genetic mechanisms. Safflower exhibits a C_3 type of photosynthesis and conserves water under drought conditions through stomatal closure and the maintenance of osmotic pressure. Owing to its deep root system, wax-coated leaves, and low transpiration coefficient, the crop consumes approximately 300-350 mm of water during the growing season. Its tolerance to salinity is associated with the compartmentalization of sodium ions within cells and enhanced proline synthesis. The seeds contain 35-40% oil and 15-21% protein, with a particularly high content of linoleic acid (omega-6). It has been demonstrated that safflower is a crop of considerable importance for the reclamation and utilization of saline and drought-affected lands under conditions of climate change.

Keywords: *Carthamus tinctorius* L., safflower, drought tolerance, photosynthesis, osmotic adjustment, antioxidant defense, molecular genetics.

ФИЗИОЛОГИЯ САФЛОРА (*CARTHAMUS TINCTORIUS* L.)

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Аннотация. Сафлор (Carthamus tinctorius L.) - одна из засухоустойчивых масличных культур, выращиваемых в засоленных и засушливых регионах Узбекистана. В данной статье представлен обзор морфологического строения сафлора, а также его фотосинтетических характеристик, водного и минерального обмена, гормональной регуляции, стрессоустойчивости и молекулярно-генетических механизмов. Сафлор обладает C_3-типом фотосинтеза и сохраняет воду в условиях засухи за счет закрытия устьиц и поддержания осмотического давления. Благодаря глубокой корневой системе, покрытым воском листьям и низкому коэффициенту транспирации, культура потребляет примерно 300-350 мм воды в течение вегетационного периода. Ее толерантность к засолению связана с компартментализацией ионов натрия внутри клеток и усилением синтеза пролина. Семена содержат 35-40% масла и 15-21% белка, с особенно высоким содержанием линолевой кислоты (омега-6). Было доказано, что сафлор является культурой, имеющей большое значение для рекультивации и использования засоленных и засушливых земель в условиях изменения климата.

Ключевые слова: Carthamus tinctorius L., сафлор, засухоустойчивость, фотосинтез, осмотическая адаптация, антиоксидантная защита, молекулярная генетика.

Introduction

Safflower (*Carthamus tinctorius* L.) belongs to the family Asteraceae and the genus *Carthamus* L. A total of 19 species of *Carthamus* are known, of which only one species, *Carthamus tinctorius*, is cultivated. Safflower is considered a highly important and promising crop for the arid conditions of Central Asia, particularly for rainfed (dryland) farming systems. It is one of the most ancient cultivated plants, although its large-scale cultivation remains limited. The main regions of its cultivation are Ethiopia, Afghanistan, and Central Asia, including southern Kazakhstan, Uzbekistan, Tajikistan, and parts of Kyrgyzstan. In Uzbekistan, the cultivated area of safflower reached approximately 37 thousand hectares in 1998; currently, it is grown on about 11-13 thousand hectares, mainly on rainfed lands. The average seed yield is 11-12 centners per hectare under rainfed conditions and 19-21 centners per hectare under irrigated conditions [4].

Nowadays, the importance of safflower as an oilseed crop is increasing. Safflower oil is consumed as an edible oil alongside other vegetable oils. In terms of quality, it is slightly inferior to sunflower oil. The petals of safflower flowers can be used as a substitute for saffron. The seeds are also used as feed for poultry. The oil content of the seeds ranges from 30 to 40%. Safflower plays a significant role in agriculture, as it is one of the most drought-tolerant crops and is considered a key crop for rainfed agriculture in Central Asia. In the wild, it is widely distributed across the desert and foothill regions of Uzbekistan [41, 50, 43].

Safflower (*Carthamus tinctorius* L.) is an annual plant with an average growth period of 130-150 days. It has a branching, herbaceous stem, and the general appearance of the plant resembles thistle-like species. The seeds are small in size and morphologically similar to those of sunflower. The plant possesses a well-developed taproot system that penetrates the soil to a depth of approximately 2-3 meters, with strongly developed lateral roots. This extensive root system enables the plant to absorb water and nutrients from deeper soil layers. The stem is glabrous, highly branched, robust, and cylindrical in shape. Plant height varies depending on cultivar and agronomic practices, typically reaching 80-120 cm. Lateral branches, measuring 15-20 cm in length, are formed on the main stem. Leaves are sessile, glabrous, with a width of 2.5-5 cm and a length of approximately 10-15 cm. Leaves are generally larger and more numerous on the lower part of the stem, gradually decreasing in size and becoming narrower toward the upper parts of the plant. The involucral bracts surrounding the flower head are ovate and rigid in structure. Leaf spinescence is a species-specific trait that increases from the lower to the upper parts of the plant in spiny forms. The floral structure of safflower resembles that of sunflower. The flowers are typically arranged in circular, flat capitula (heads), which are formed at the tips of the main stem and lateral branches. Primary branches flower earlier than secondary ones. Flowering begins at the terminal capitulum of the main stem and subsequently continues on the primary, secondary, and tertiary branches in sequence. The overall flowering period ranges from 10 to 40 days, depending on environmental conditions. Capitulum diameter varies from 1.25 to 4.0 cm. Flowering within a single capitulum usually begins at the margins and progresses toward the center, lasting approximately 3-4 days. The seed is enclosed by a thick, hard, fibrous hull, which generally accounts for about 50% of the total seed weight. The hull is typically white in color. Although the hull is generally non-spiny, fine and sparse spines may occur in some spiny forms. The 1,000-seed weight ranges from 40 to 50 g. Safflower is a widely cultivated oilseed crop in Central Asia and is characterized by high drought tolerance. In Uzbekistan, safflower is grown as an oilseed crop, as feed for poultry, and for use in medicine and cosmetics. The seeds contain 30-40% semi-drying oil, which is used in food production, including margarine manufacturing. In addition, safflower seeds are rich in protein, fats, and carbohydrates [2, 17, 34].

Safflower seeds contain 35-40% oil, of which 70-78% is linoleic acid (omega-6) [14]. These characteristics place safflower oil on a comparable level with sunflower and olive oils in terms of nutritional value. The flower petals contain red and yellow pigments, which are widely used as natural colorants in the food, cosmetic, and textile industries.

Climate change and soil salinization are intensifying as global challenges. According to FAO reports, by 2050 a significant proportion of the world's irrigated agricultural land may become unproductive due to salinization [13]. For this reason, FAO and ICARDA have officially designated safflower as a "climate-resilient strategic oilseed crop for saline environments" [20]. In addition, the *Strategy for Agricultural Development of the Republic of Uzbekistan until 2030* identifies safflower as one of the key crops for the reclamation and sustainable use of saline and drought-affected lands [33].

In recent years, extensive research has been conducted worldwide on the physiology and molecular genetics of safflower. In particular, the roles of abscisic acid (ABA), proline biosynthesis, and the antioxidant defense system under drought and salinity stress conditions have been studied in depth.

This article aims to address the following issues based on contemporary scientific approaches:

- deep root system and mechanisms of water-use efficiency;
- control of transpiration through stomatal regulation;
- efficiency of C_3 photosynthesis;
- fundamental mechanisms of salinity tolerance.

This article presents the scientific basis for expanding the cultivation of safflower in saline and drought-prone lands of Uzbekistan's agricultural sector.

Safflower (*Carthamus tinctorius* L.) is an annual plant with a height ranging from 30 to 150 cm, depending on planting density and nutrient availability [1]. The stem is erect and strongly branched; the presence of rigid fibers within the stem protects the plant from wind and mechanical damage. The stem surface is smooth or slightly pubescent, with a diameter of 1-2 cm [31].

Leaves are arranged alternately along the stem, measuring 5-15 cm in length and 1-4 cm in width. They are lanceolate or elongated in shape and are usually spiny, although spineless forms also occur depending on the cultivar. The leaf surface bears fine hairs (trichomes), which reduce transpiration by 20-30% [8]. The total leaf area of a single safflower plant ranges from 0.5 to 1.0 m^2.

The root system is one of the most important adaptive traits of safflower. The main taproot penetrates the soil to a depth of 2.5-3.5 m, while lateral roots extend mainly within the 0-60 cm soil layer [10]. The total root length may reach up to 10-15 km, which is approximately 2.5 times greater than that of cotton [28]. Such a root architecture enables the plant to survive drought conditions without irrigation for up to one month.

The flowers are of the capitulum type, characteristic of the Asteraceae family, and are orange, red, or white in color. The capitula have a diameter of

1.6-3.5 cm [30]. Each capitulum contains an average of 35-50 florets, and a single plant produces between 3 and 30 capitula. The flowering period lasts up to one month. Pollination occurs mainly through insects, although the plant also exhibits self-pollination capability [26]. Flowering typically takes place from late June to mid-July.

The seed is a hard-coated achene, white or light brown in color, measuring 6-8 mm in length and 3-5 mm in width. The thousand-seed weight ranges from 32 to 52 g (25-60 g in some cultivars) [12]. The seed coat is thick and fibrous, and the oil content of the seeds in Uzbek cultivars may reach 48-58%.

The chromosome number is 2n=24, indicating a diploid genome with high genetic stability. There are 25 wild relative species, with which hybridization is possible [15]. Cultivars grown in Uzbekistan (e.g., “Nurafshon,” “Zarafshon,” and “Suvchi”) have a plant height of 80-120 cm, produce 20-35 capitula per plant, and yield 15-22 centners per hectare [45].

Safflower belongs to the C_3 photosynthetic type and assimilates CO_2 via ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), producing 3-phosphoglycerate as the first stable product of carbon fixation [11]. Maximum photosynthetic intensity is observed at temperatures of 26-33 °C and light intensities of 350–500 μmol m^{-2} s^{-1} [29]. Under drought conditions, the photosynthetic rate decreases by 26–65%; however, activation of the antioxidant system (superoxide dismutase-SOD, catalase-CAT, and ascorbate peroxidase-APX) prevents damage to cell membranes [11].

The transpiration coefficient is very low, ranging from 280 to 350, indicating water consumption that is 2.0-2.5 times lower than that of cotton and 1.6-1.8 times lower than that of sunflower [39]. Stomata close rapidly under the influence of abscisic acid (ABA), resulting in reduced transpiration during the hottest parts of the day [3].

The growing season lasts 120-160 days in local landraces (early-maturing cultivars 105-115 days; medium-maturing cultivars 120-130 days). The optimal growth temperature is 23-32 °C; however, seedlings can tolerate frost down to -7 to -8 °C [22]. The salinity threshold is 11 dS m^{-1} (ECe); above this level, germination decreases below 20-25% [16].

The chemical composition of *Carthamus tinctorius* seeds is as follows: oil 23-36.5%, protein 16-21%, fiber approximately 28%, and ash 1.55-2.0%. The oil is rich in linoleic acid (55-77%), followed by oleic acid (11-18%), palmitic acid (5-8%), and stearic acid (1.9-3%). The α-tocopherol content of the oil may reach 46-71 mg per 100 g [40, 35].

Safflower has very low water requirements: during the entire growing season, 300-380 mm of water is sufficient, of which 60-70% is absorbed from moisture stored in deeper soil layers. On average, 320-350 m³ of water is required to produce one ton of seed yield.

Safflower exhibits moderate to high resistance to diseases and pests, which is one of the main reasons for its wide cultivation in hot and arid climates.

The principal diseases of current importance include:

Fusarium wilt - the most dangerous disease; it is a vascular wilt associated with the xylem system. However, it does not develop under dry conditions (soil moisture <45%) [25].

Alternaria leaf spot (*Alternaria carthami*) - causes dark lesions on leaves; the pathogen kills plant cells and utilizes their contents as a nutrient source. The disease becomes active under high humidity conditions (above 70%) and may reduce yield by up to 30% [21].

Rust (*Puccinia carthami*) causes reddish-brown pustules on leaves and stems and inflicts damage primarily during cool and humid spring conditions. Moderate infection may reduce yield by 10-20% [7].

Phytophthora root rot (*Phytophthora drechsleri*) occurs mainly in heavy soils and in areas with excessive moisture accumulation or poor drainage.

Safflower cultivars resistant to these diseases exhibit 7-9 points of resistance (on a 9-point scale) against *Fusarium* wilt and Alternaria leaf spot. Under the climatic conditions of Uzbekistan, *Fusarium* damage generally remains limited due to the hot and dry summer environment.

Major Pests

Safflower fly (*Acanthiophilus helianthi*) is the most destructive pest and can reduce seed yield by 30-50%. Aphids (*Aphis fabae*, *Uroleucon carthami*) feed on leaf sap and act as vectors of viral diseases.

Lepidopteran larvae (*Helicoverpa armigera*, *Spodoptera exigua*) damage the capitula by feeding on developing tissues. Drought and high temperatures significantly suppress pest development; at temperatures above 35 °C, larvae of the safflower fly fail to survive. Spiny safflower cultivars provide a mechanical barrier against aphids and lepidopteran larvae [24, 36, 38, 42].

Integrated Protection Measures

Crop rotation (once every 2-3 years) significantly reduces the incidence of diseases. Application of phosphorus–potassium fertilizers ($P_{60}K_{40}$) enhances plant immunity and resistance. Biological agents (*Trichoderma viride*, *Bacillus thuringiensis*) serve as effective alternatives to chemical pesticides [18, 19, 44].

Under the conditions of Uzbekistan, yield losses caused by safflower diseases generally range from 5 to 15%, while damage from insect pest accounts for 8 to 20%, which is considerably lower than that observed in cotton and sunflower cultivation.

At the global level, the largest genetic collection of safflower is conserved at USDA-ARS (United States Department of Agriculture - Agricultural Research Service), which, as of 2024, includes 3,126 accessions. In Uzbekistan, safflower genetic resources are maintained at the Institute of Genetics and Experimental Plant Biology of the Academy of Sciences of the Republic of Uzbekistan and at the Agricultural Research and Production Center. These collections comprise a total of 482 local and foreign accessions, including 127 local populations and 355 foreign cultivars and breeding lines [23, 32].

The most drought-tolerant and high-yielding safflower accessions, based on evaluations conducted during 2023-2024, include:

✔ Milutinsky 114 - a cultivar widely cultivated in Uzbekistan since the Soviet period;

✔ Jizzakh-1 - a selected line with confirmed high yield performance;

✔ Izzah-1 - a genotype introduced through breeding programs;

✔ Moydor - a cultivar developed and registered as a result of selection efforts.

The national collection contains 28 high-oleic accessions (75-82% oleic acid) and 64 spineless accessions, which are currently being utilized as donor material in future breeding programs.

Accessions preserved in the collection are regenerated every 5-7 years, and seeds are stored under long-term conservation conditions at -18 °C.

Safflower is a diploid species with a genome size of approximately 1.5 Gbp and a chromosome number of 2n = 24. Over the past decade, complete genome sequencing of safflower has been achieved, and in 2022 the genomic data were deposited in the NCBI database. These advances have enabled the identification of new molecular markers and functional genes, thereby significantly enhancing opportunities for modern breeding and genetic improvement [9, 47].

Key Genes Associated with Drought and Salinity Tolerance

1. CtHDZIP26 - Liu et al., 2025, *BMC Genomics*: identification of the HD-ZIP gene family and its expression under drought stress; 2. CtWRKY55 - member of the WRKY gene family involved in stress-responsive regulatory pathways; 3. P5CS1 - plays a central role in proline biosynthesis and drought tolerance; 4. SOD1 (Cu/Zn superoxide dismutase) - involved in antioxidant defense mechanisms; 5. ABA2 - participates in abscisic acid biosynthesis and stress signal transduction.; . CtFLS1 - involved in flavonol biosynthesis and protection against abiotic stress.; Ser/Thr protein kinase - stress-responsive genes identified through genome-wide association studies (GWAS); 8. Zinc finger proteins - GWAS-identified genes

associated with stress responses; 9. PAL (phenylalanine ammonia-lyase) - contributes to antioxidant defense under salinity stress [27, 48, 49].

Genes associated with oil quality:

CtFAD2-1 and CtFAD2-2 regulate linoleic acid biosynthesis. Targeted knockout of these genes using CRISPR/Cas9 technology has increased oleic acid content from 16-18% to 75-82%.

CtFATB, which is involved in palmitic acid biosynthesis, shows reduced expression in high-oleic safflower cultivars [5, 6, 37, 46].

Recent Advances in Safflower Research:

-In 2021, the first commercially viable high-oleic safflower cultivar (82% oleic acid) was developed in China through CRISPR-mediated knockout of the CtFAD2 gene.

-In 2023, the CtABF3 transcription factor was fully cloned in Uzbekistan, and its functional role in stress response was characterized.

-In 2024, scientists from India and Iran successfully introduced the CtDREB2B gene from safflower into cotton, achieving a 38% increase in drought tolerance.

In Uzbekistan, molecular genetic research on safflower has been actively conducted within the framework of the project “Molecular Evaluation of Safflower Genetic Resources” during 2022-2025. A total of 480 accessions were genotyped using SSR and SNP markers, leading to the identification of 86 drought-tolerance-associated markers, which are currently being utilized in marker-assisted selection (MAS) programs.

Future research directions focus on the development of new drought-tolerant and high-oil safflower cultivars within 3-5 years through the application of genomic selection (GS), as well as the pyramiding of spinelessness and high-oleic acid genes to combine agronomic adaptability with superior oil quality.

Comprehensive physiological, morpho-biological, and molecular-genetic investigations have unequivocally demonstrated that safflower (*Carthamus tinctorius* L.) is one of the most promising oilseed and strategic crops for Uzbekistan and other arid regions. Its deep and well-developed root system, low transpiration coefficient, and highly efficient antioxidant defense mechanisms enable the crop to conserve water two- to three-fold under drought conditions. Salinity tolerance is primarily associated with sodium ion compartmentalization and the accumulation of key osmoprotectants such as proline and glycine betaine.

With regard to oil quality, safflower seeds contain up to 78% linoleic acid, while recent biotechnological advances have enabled the development of cultivars with oleic acid content reaching 82%, rendering safflower a competitive alternative to sunflower and olive oils.

The expansion of safflower cultivation on 48% of Uzbekistan's saline and drought-affected lands would not only enhance national food security, but also mitigate cotton monoculture dominance, improve soil fertility, and substantially conserve water resources. Over the next 5-7 years, the integration of genomic selection and marker-assisted breeding is expected to deliver new cultivars fully adapted to local agro-ecological conditions, with yields of 25-30 quintals, oil content exceeding 60%, and exceptionally high tolerance to drought and salinity.

In conclusion, safflower should be regarded not merely as an alternative crop for present agricultural systems, but as a strategic species capable of ensuring the sustainable development of Uzbekistan's agriculture under conditions of climate change.

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According to the decision of the Higher Attestation Commission of the Republic of Uzbekistan dated March 31, 2023 No. 332/5/6, the publication of the main scientific results of dissertations in biological sciences is included in the list of recommended national scientific publications.

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Qog`oz bichimi 60x84 1/16. Palatino Linotype
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Ofsåt uslubida oq qog`ozda chop etildi.
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