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REVIEW

Current Status and Prospects for Perennial Crop Breeding

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Abstract

Annual crops, cultivated on 60%-80% of global cropland, form a critical cropping system that supports the majority of food production but requires significant inputs, whose deficiency can lead to soil and nutrient loss. In contrast, perennial cultivation systems, which are planted once and harvested repeatedly, have shown the potential to reduce inputs and help retain soil carbon. Therefore, the primary breeding method for developing perennial major crops has been interspecific hybridization between conventional annual varieties and their relative species. Research has focused on minor crops, such as buckwheat, because their perennial species exhibit waterlogging tolerance. However, developed perennial varieties and breeding lines face more challenges than annual crops, including hybrid sterility, low productivity, susceptibility to plant pests and diseases, and weed potential. Additionally, frost or soil freezing tolerance traits are essential for wintering, especially at high altitudes and in high-latitude regions. In this review, we highlight the differences between annual and perennial species, summarize studies that advance perennial traits and hybrid development, and introduce the latest domesticated perennial hybrids. To maintain stable food production, the development of new breeding technologies for perennial crops are a promising option.

Discipline: Crop Science
Additional key words: interspecific hybridization, minor crops

Introduction

Annual crops that were independently domesticated on various continents at the onset of the Neolithic revolution are now cultivated on 60%-80% of the world's croplands and provide 80% of the global food supply (Pimentel et al. 2012). However, modern high-yielding annual crops generally require significant inputs of energy, pesticides, fertilizers, and, in some cases, labor to achieve optimal productivity (Cox et al. 2006). The combination of persistent soil disturbance and high input levels often undermines essential ecosystem services, pushing many farmlands beyond sustainable limits (Cox et al. 2006, Wan 2018, Crews et al. 2018). Furthermore, annual crops generally provide only sporadic plant cover for the soil throughout the year. This intermittent coverage exposes bare soil to heavy rainfall, leading to significant soil and nutrient loss. Consequently, this erosion diminishes soil fertility and contributes to the eutrophication of aquatic ecosystems (Rabalais et al. 2007, Culman et al. 2013, Jungers et al. 2019). This condition is particularly prevalent on marginal lands, which currently sustain 50% of the global population and face an increased risk of further degradation under annual cropping practices (FAO 2009, Monfreda et al. 2008). Additional significant risks, such as cold damage caused by volcanic eruptions, can lead to severely poor harvests, resulting in starvation (Kondo 1985, Yamakawa 1993). Rapid and drastic weather fluctuations have recently hindered the stable production of first-year grains, making advanced, stable grain production more pressing.

Perennial crops offer distinct advantages over annual crops in preserving crucial ecosystem functions. Such crops typically possess an extended photosynthetic period, which improves annual light capture and boosts

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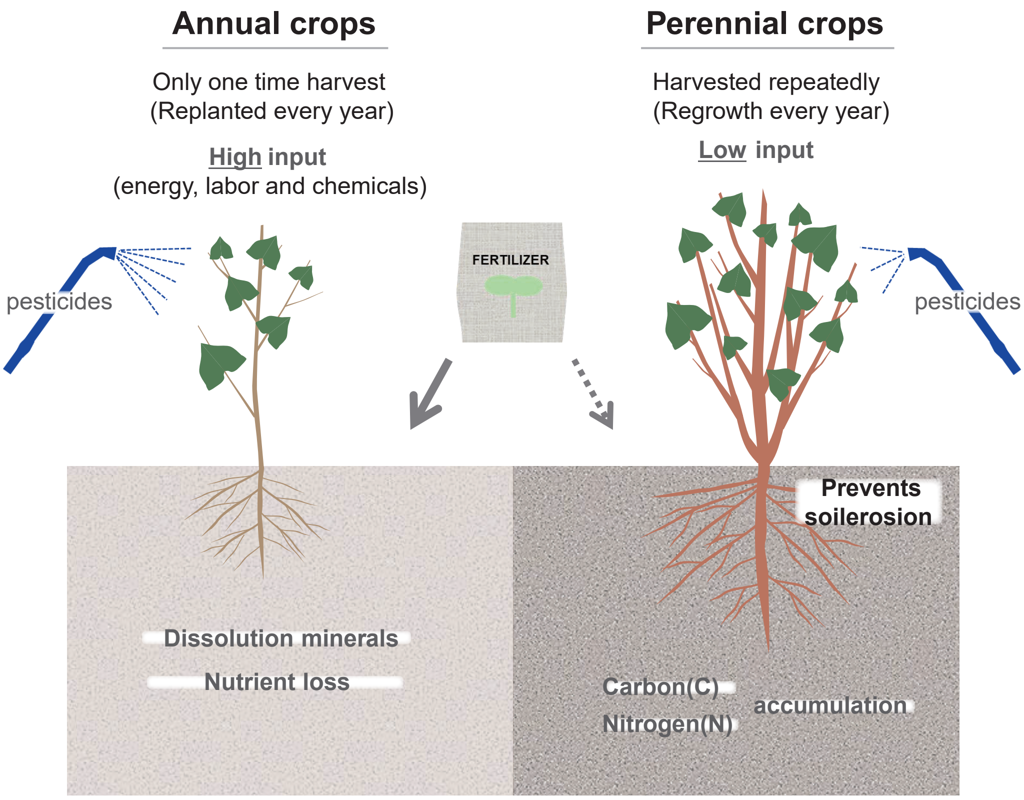

Fig. 1. Benefit of a perennial cultivation system compared to an annual cultivation system from the perspective of sustainability in agricultural production

overall productivity (Dohleman & Long 2009). Along with providing permanent living cover, the deep root systems of perennial crops have been demonstrated to enhance nitrogen (N) retention and promote soil carbon accumulation (Culman et al. 2013, Jungers et al. 2019, van der Pol et al. 2022, de Oliveira et al. 2018). In addition, these deep root systems may ultimately reduce the need for fertilizers, pesticides, and labor inputs (Crews et al. 2018). Perennial cropping systems can be managed to produce grains and forage in mixed crop-livestock systems (Pimentel et al. 2012, Bell et al. 2008, Mosier et al. 2021, Glover et al. 2010, Glover & Reganold 2010). By enhancing labor efficiency and soil quality, perennial cropping systems not only improve farmers' livelihoods but also support the ecological systems necessary for sustaining long-term productivity (Glover et al. 2010, Glover & Reganold 2010, Tilman et al. 2009). Issues in Japanese agriculture include a decreasing number of farmers, the expansion of abandoned land, and the rising cost of materials (MAFF 2024). Thus, suitable perennial crops must be developed for Japan that will offer offsetting advantages. Additionally, the Japanese environment is characterized by frost, frozen soil, and heavy rainfall, necessitating the cultivation of perennial grains that can withstand these conditions. Perennial buckwheat in particular has the greatest potential for cultivation because of its tolerance to frost, water, heat, and disease in humid subtropical regions, where other perennial crops such as rice are unsuited because they cannot overwinter. Thus, this study also focused on the development of perennial buckwheat.

Focusing on major crops and oilseeds such as wheat, sunflower, barley, sorghum, and rice, researchers from various countries are working on developing perennial versions of these annual crops through two primary breeding strategies: de novo domestication and interspecific hybridization (Piper & Kulakow 1994, Hu et al. 2003, Cox et al. 2010, Zhang et al. 2023). While these efforts focus primarily on major crops, we believe that it is necessary to expand their scope to minor crops as well. Most minor crops have been cultivated in marginal land because they can grow under conditions where major crops such as rice or wheat cannot. Therefore, the perennialization of minor crops should be in higher demand than major crops, as farmers growing minor crops desire crops that require less time and effort.

In this review, we present the current status, research issues, and prospects of perennial crop breeding, including perspectives on frost, soil freezing, and heavy rainfall, and extend the scope to cereal crops.

Table 1. Benefit of a perennial cultivation system compared to an annual cultivation system from the perspective of sustainability in agricultural production

	Overwinter	Productivity	Repeated cultivation	Shattering resistance	Water tolerance	Pest and disease tolerance	Future challenges	Notes
Perennial rice	△ (Limited to frost-free areas between 40°N and 40° S)	◎ PR23:ARDiantun 502= 6.9:7.0Mg ha^{-1} (average production)	Twice a year for up to four years (total of 8 times)	◎	◎	△ Resistant to rice yellow mottle virus (PR107)	Requires one or two-time pesticide and herbicide application	Zhang, S. et al. (2023)
Perennial wheat (intermediate wheatgrass)	○	△	Many times (although yield decreases)	◎	-	○		Cox, T. S. et al. (2002)
Perennial buckwheat	○	◎	Many times	◎	◎	○	Strong bitter taste	Chen, Q. F. (2018) Suzuki, et al. (2023a)
Perennial Job's tears	△ (Limited to tropical regions, lack of frost tolerance)	△	-	-	-	-		Murakami, M. & Harada, K. (1958)
Perennial Lupins	○	-	-	-	-	-	Contain bitter quinolizidine alkaloids	BfR (2017)

◎ : Good, ○ : Moderate, △ : Limited, ×: Poor

Carbohydrate-based crops

1. Perennial rice

Many wild and cultivated species of rice are potentially perennial species, including *Oryza sativa* (Khush 1997). However, perennial traits may not be exhibited in specific growing environments (Sakagami et al. 1999). For example, species and strains that are susceptible to low winter temperatures cannot overwinter and die, but they can survive and overwinter in the tropics and subtropics. The study by Zhang et al. (2023) provides a review of the breeding and cultivation of perennial rice (PR), which is currently considered the most widely cultivated perennial crop. Farmers show a strong preference for perennial cultivars, as their cultivation reduces labor by 58.1% and input costs by 49.2% in each regrowth cycle. In 2021, 15,333 ha of PR were cultivated by 44,752 smallholder farmers in southern China. These farmers accomplished interspecific hybridization between the annual, domesticated Asian rice cultivar *Oryza sativa* ssp. *indica* RD23 from Thailand and a wild African perennial rhizomatous species, *Oryza longistaminata*, from Nigeria through embryo rescue. Over a period of four years, PR cultivated from a single planting and irrigated produced grain in eight consecutive harvests, with an average yield of 6.8 Mg ha^{-1} per harvest. In comparison, annually replanted rice, which required additional labor and seed inputs, produced an average of 6.7 Mg ha^{-1} per harvest. In other words, the yield potential was almost the same as that of conventional cultivation for four years. They observed that despite a decreasing trend in the regrowth rate over eight seasons (four years), the panicle density per square meter and other grain yield traits remained stable. This suggests that PR possesses a capacity for regrowth and tillering, which can offset any minor reductions in plant stand that might occur during earlier regrowth cycles. However, in the fifth year (the 9th and 10th seasons), there was a significant decline in grain yield, primarily attributed to a substantial reduction in regrowth rate (below 75%), along with decreases in panicle number and spikelet number per panicle. In addition, since PR plants are killed by frost, the application range is limited to frost-free areas from 40° N to 40° S. They mentioned that one or two additional herbicide applications were required for weed control during the regrowth cycles of PR compared to retransplanted rice. Under irrigated conditions, pests such as brown planthoppers, green leafhoppers, and leaf folders can become problematic with high N application. However, these can be managed through integrated pest management by adjusting N application to better match crop demand. In rainfed cultivation, pests and diseases are generally less severe, but issues such as gall midge can arise if there is no ponded water during tiller elongation, and thrips can cause local damage. A greater concern may be insect-transmitted viruses, such as tungro and rice yellow mottle virus in Africa. However, PR107, resistant to the rice yellow mottle virus due to its *O. longistaminata* parent, has been released in Uganda. Furthermore, integrating double cropping in frost-free conditions (Yamaoka 2018) with winter rice cultivation techniques, such as winter flooding under frost conditions, could potentially enhance production stability and reduce labor requirements.

2. Perennial wheat, rye, sorghum, and maize

Many species in the Triticeae tribe are perennial (Dewey 1984). Typical examples include the genera *Hordeum*, *Elymus*, *Leymus*, *Secale*, and *Thinopyrum*. Wheat can hybridize with most of these species, and many interspecific hybrids have been developed (Dewey 1984, Kishii 2010). It has become clear that when annual wheat is crossed with perennial species, annual traits predominate in the F_1 and its amphidiploid, while all F_1 hybrids exhibit varying degrees of perenniality (Cox et al. 2002). Perennial traits of wheat are quantitative traits, and the biggest challenge in their practical application is to improve yield (Cox et al. 2002). One of the most famous perennial wheat efforts is intermediate wheatgrass [IWG; *Thinopyrum intermedium* (Host) Barkworth & D. R. Dewey subsp. intermedium], commercialized under the tradename of Khanza (The Land Institute 2024). In variety trials conducted across Minnesota, MN-Clearwater (IWG) yielded an average of 696 kg ha^{-1} (621 lb ac^{-1}) of grain with minimal lodging and negligible disease levels. The highest grain yields were observed during the first two years, whereas the third-year yields showed a significant decrease, averaging a 77% reduction from the initial two years (Prabin et al. 2020). IWG, as a novel grain crop undergoing domestication, lags behind annual grains in terms of yield, seed size, and other agronomic traits. To improve these traits, association mapping using 24,284 genome-wide SNP markers identified 30 main QTL (Quantitative Trait Loci) across all tested environments and 32 QTL-by-environment interactions at each environment (Prabin et al. 2024). Genomic selection has also been conducted (Chapman et al. 2022). Similar to perennial wheat, studies are being conducted to develop perennial grain crops such as rye (Gruner & Miedaner 2021), sorghum (Washburn et al. 2013, Cox et al. 2018, Habyarimana et al. 2020), and maize (Westerbergh & Doebley 2004, Swentowsky et al. 2021) through the hybridization of annual species with their perennial relatives. Previous studies reported that certain cultivars of rye exhibit reduced fertility, which is attributed to the formation of chromosomal multivalents (Gruner & Miedaner 2021). However, recent research suggests that this fertility reduction may be primarily associated with the self-incompatibility locus. Notably, chromosomal cosegregation events, such as the formation of multivalents, were not observed in these lines (Gruner & Miedaner 2021). For sorghum, although hybrid progeny often face challenges in surviving cold temperate climates, the development of high-yielding perennial varieties appears feasible under warmer conditions (Cox et al. 2018). In maize, genetic analyses utilizing populations derived from crosses between the annual species *Zea mays* and its perennial relative *Zea diploperennis* have facilitated the identification of QTLs associated with traits related to perennial regrowth (Swentowsky et al. 2021). Furthermore, perenniality has been characterized as a polygenic trait, suggesting that its successful introduction necessitates targeting multiple genetic loci (Westerbergh & Doebley 2004).

3. Perennial buckwheat

Major buckwheat crops include the annual species, common buckwheat (*Fagopyrum esculentum*) and tartary buckwheat (*Fagopyrum tataricum*). Annual buckwheat is a valuable food source and a suitable crop for cultivation. As a food, buckwheat contains high-quality protein and rutin, which may have body weight reduction effects in clinical trials (Nishimura et al. 2016). It has been grown in deserted agricultural land and in hilly and mountainous areas, either as an alternative to rice or as part of a crop rotation system. In addition, buckwheat is recognized as a labor-saving crop due to its ability to grow with low fertility and minimal pesticide use, and its short growing period, which typically lasts only two or three months. However, in China, the largest buckwheat-producing country, the number of farmers growing buckwheat is decreasing every year. This decline is due to the relatively low grain yield and the shift toward high-income alternative crops such as soybeans and corn, which are being cultivated to replace buckwheat. Thus, buckwheat farmers tend to leave the farm, and the cultivation area is decreasing. In Japan, a decrease in productivity caused by heat stress, possibly associated with preharvest sprouting, combined with the anticipated aging population of agricultural workers, has made establishing a more labor-saving and stable productivity system necessary. The low grain yield of buckwheat is caused by its sensitivity to weather conditions. In particular, recent abnormal weather conditions caused by global warming have resulted in many cases of wet injury due to large typhoons and localized torrential rains. Therefore, we need innovative buckwheat varieties that have moisture resistance. However, conventional breeding using mutations among cultivated species is limited. In contrast, perennial buckwheat, the *Fagopyrum cymosum* complex—classified as diploid *Fagopyrum megaspartanium*, diploid *Fagopyrum pilus*, and allotetraploid *F. cymosum* (Chen 1999)—are wild relatives with waterlogging resistance due to their indigenous growth in damp ground, such as valleys (Zhou et al. 2018). A recent study demonstrated that a wintering perennial buckwheat, *F. cymosum*, can survive under waterlogged conditions (Suzuki et al. 2024). *F. cymosum* is found in regions where frost and soil freezing occur, suggesting that it likely possesses tolerance to these conditions. Wild perennial buckwheat has not been used for cultivation due to its unfavorable traits, such as scrawny seeds, shattering, strong bitterness (Suzuki et al. 2023b), seed dormancy, and its use as a green vegetable or medicinal crop in some areas (Suvorova 2016, Chen et al. 2018). While the mechanism of waterlogging resistance in perennial buckwheat has not been clarified, introducing the beneficial traits of perennial buckwheat into common buckwheat or tartary buckwheat could make it possible to develop cultivation species with enhanced moisture resistance. Therefore, we need to develop buckwheat varieties with beneficial traits adapted to climate fluctuations by obtaining innovative breeding materials and increasing the range of mutations through interspecific hybridization.

Interspecific hybridization of buckwheat has been attempted for a long time (Morris 1951, Nagatomo 1961), and interspecific hybridization among cultivated species and *F. cymosum* has been tried to improve its traits. However, only three perennial hybrids with seed fertility have been reported (Chen et al. 2018, Suzuki et al. 2023a). Krotov (1973) reported the development of an allopolyploid hybrid between *F. tataricum* and *F. cymosum* for the first time, called *Fagopyrum giganteum*. However, this hybrid was an annual buckwheat. Most hybrids from interspecific hybridization are known to become sterile due to abnormal meiosis (Chen 2019, Sugiyama 2023). Thus, interspecific hybridization by embryo rescue, which regenerates plants by cultivating embryos or ovules rescued from pollinated cells before they degenerate, has been primarily attempted (Asaduzzaman et al. 2009, Hirose et al. 1991). By embryo rescue, many researchers attempted to make hybrids between *F. cymosum* and common buckwheat, among other native species (Hirose et al. 1991, Suvorova et al. 1994, Woo et al. 2018, Yui et al. 2005, Minami 2009, Matsushima 2013, Fesenko 2022, Sugiyama 2023). However, almost all hybrids exhibit remarkable sterility, and only a few can be cultivated using subcultures. Fesenko et al. (2022) reported the successful production of an F1 hybrid clone using the embryo rescue technique. The plants occasionally produced seeds without pollination by other plants, which usually did not survive, but two of the seeds were viable. Conversely, Chen et al. (2018) reported the successful creation of the perennial hybrid, *F. tatari-cymosum* Q. F., by crossing artificial tetraploid *F. tataricum* and *F. cymosum*. The hybrid exhibits fertility, and progeny was obtained from it. The new species exhibits traits such as three growing seasons a year, self-fertilization, and minimal shattering; its three cultivation varieties have been spreading in China. In addition, Chen reported that F_1 perennial hybrids—*F. giganteum* × *F. cymosum* Hongxin Jingqiao, *F. giganteum* × *F. megaspartanium*, *F. giganteum* × rice tartary buckwheat, and *F. giganteum* × common buckwheat—obtained until 2014, were completely sterile. Therefore, by backcrossing several species with these hybrids, Chen succeeded in making a perennial hybrid of *F. giganteum*/*F. megaspartanium*/*F. megaspartanium*, which has strong perennial traits derived from *F. megaspartanium*. In addition, cytological observation of meiotic chromosomes in these perennial hybrids revealed that sterile pairs of hybrids are attributed to monovalents at meiosis M_1 (Chen 2019). Suzuki et al. (2023a) created a sterile perennial hybrid by crossing *F. cymosum* and tartary buckwheat, an artificial tetraploid bred from Manten kirari, which possesses a mutation in rutinosidase activity related to bitterness (Suzuki et al. 2023b). This hybrid is expected to have practical waterlogging resistance and to develop water-tolerant varieties for food through backcrossing or crossing with other buckwheat species.

These perennial hybrids exhibit unfavorable traits, such as shattering habits related to the abscission layer, a strong bitter taste, limited flowering time due to sensitivity to photoperiod, low productivity inherited from perennial buckwheat, and a risk of becoming a weed due to sprouting from shattering seeds or wintering roots. Therefore, there are significant challenges to the practical application of perennial hybrids (Chen et al. 2018). However, if we improve these unfavorable traits through breeding, using perennial buckwheat can enhance productivity. This improvement is less likely to be affected by excess moisture injury. In addition, it is expected that we will develop a system that allows repeated harvesting from a single plantation sowing, similar to the ratooning system used for sugar cane and rice, including perennial varieties (Zhang et al. 2023, Nakano et al. 2020). In other words, by using perennial hybrids, we can create labor-saving crops that surpass conventional annual buckwheat. In the future, we will need to develop new species that are adapted to farmers' demands and climate changes. This includes using current perennial hybrids and clarifying the mechanisms behind excess moisture injury and winter freeze resistance of perennial buckwheat.

4. Job's tears

Job's tears (*Coix lacryma-jobi*), also referred to as adlay or adlay millet, is a tall, grain-bearing perennial plant belonging to the Poaceae family (grass family). Native to Southeast Asia, including the Indian subcontinent, Job's tears was introduced to northern China and Japan in ancient times and is cultivated as an annual in many other parts of the world. The species comprises a wild type and a cultivated form. The wild variety, *C. lacryma-jobi var. lacryma-jobi*, produces hard-shelled pseudocarps that are pearly white and oval-shaped and are widely used as beads for crafting prayer beads, rosaries, necklaces, and various decorative items. The cultivated variety, *C. lacryma-jobi* var. *ma-yuen*, is harvested as a cereal crop, has a soft shell, and is used medicinally in parts of Asia. Throughout East Asia, Job's tears is available in dried form and cooked as a grain. Job's tears grains are widely eaten as a cereal. The cultivated varieties have soft shells and can be easily cooked into gruels and other dishes (Corke et al. 2015). In Japan, the wild variety, *C. lacryma-jobi* var. *lacryma-jobi*, is empirically regarded as a perennial, whereas var. *ma-yuen* is considered an annual. Murakami & Harada (1958) developed *C. lacryma-jobi* var. *ma-yuen* with perennial traits for breeding as feed for the green harvest; hybridization of *C. lacryma-jobi* var. *lacryma-jobi* with *C. lacryma-jobi* var. *ma-yuen* has been shown to increase overwintering ability after the F1 generation. These experiments were conducted in a frost-prone area. While *C. lacryma-jobi* var. *ma-yuen* is capable of overwintering in tropical regions, most individuals cannot survive in regions with frost. This suggests that frost resistance is a critical factor in adapting to such environments. Some hybrid strains have demonstrated vigorous vegetative growth (Murakami & Harada 1958). To establish their potential as perennial grains, future research should focus on enhancing seed yield, optimizing plant architecture, selecting for softer hulls, and improving disease resistance. Furthermore, var. *lacryma-jobi* is characterized by a relatively high amylose content in its seed starch, whereas var. ma-yuen exhibits waxy starch properties. Since hybrid progeny are expected to display diverse starch characteristics, it will be essential to develop food processing methods that effectively utilize these traits.

Crops for protein material

1. Legumes

Soybeans (*Glycine max*) are one of the most widely recognized legumes, valued for their role as a primary source of dietary protein. While soybeans serve as an oilseed crop and a protein source, this section focuses on their potential for perennial crop breeding. Soybeans belong to the subgenus *Soja* within the genus *Glycine*. In addition to *Soja*, wild species classified under the subgenus *Glycine* are known, including perennial species such as *Glycine tabacina* and *Glycine tomentella*, which are native to regions such as Australia and Taiwan (Kaizuma et al. 2003). Although it is generally understood that soybeans cannot overwinter in frost-prone regions, comprehensive studies on frost tolerance, particularly for species such as *G. soja*, remain limited. This leaves open the possibility of developing perennial soybean varieties through interspecific hybridization and related approaches. Other leguminous species, such as *Psophocarpus tetragonolobus* (the winged bean), are perennial in tropical regions. Winged beans are utilized as a vegetable, using its young pods, and as a grain crop, with mature seeds notable for their high protein content. However, challenges remain for its domestication, including improving traits such as climbing growth habits and adaptability for wider cultivation.

Lupins belong to the genus *Lupinus* (tribe *Genisteae*) and are promising protein sources. Lupins consist of over 280 species, including annual herbaceous plants and perennial herbaceous or woody shrubs. Among the numerous lupin species, some, such as *Lupinus polyphyllus*, exhibit perennial growth traits. However, lupin seeds most commonly contain bitter quinolizidine alkaloids, which are toxicologically significant and can cause poisoning in humans, affecting the nervous, circulatory, and digestive systems (BfR 2017). These are referred to as bitter lupins. In contrast, certain lupin varieties, such as white lupin (*Lupinus albus*), which is an annual species, produce seeds with low alkaloid levels. These low-alkaloid varieties, known as sweet lupins, are suitable for human consumption without requiring a debittering process. To develop a perennial, nontoxic lupin variety, interspecific hybridization between perennial and nontoxic lupins represents a promising strategy.

Crops for oil production

1. Soybean, rape, and sunflower

Palm kernel, soybean, rapeseed, and sunflower account for a large portion of the world's seed-based oil production (OIL WORLD 2025). Oil palm (*Elaeis guineensis* and *Elaeis oleifera*) is a perennial woody plant cultivated primarily in tropical regions. Since these species are not cold-tolerant, crossbreeding with cold-tolerant species may be necessary to expand their growing areas. Soybeans are described in the previous section. Rapeseed oil is primarily grown in its winter variety across most of Europe and Asia because vernalization is necessary to initiate flowering. Conversely, spring rapeseed is grown in Canada, northern Europe, and Australia because it lacks winter hardiness and does not depend on vernalization. Spring rapeseed is planted in spring, and stem growth begins immediately after germination (Snowdon et al. 2006). Oilseed rape (*Brassica napus*, AACC, $2n = 38$) is a winter oil crop that is predominantly annual. However, certain related species, such as tuber mustard (*Brassica juncea*, AABB, $2n = 36$), exhibit a perennial growth habit. The introduction of novel alleles into *B. napus* has been challenging due to hybridization barriers, including hybrid embryo abortion. Despite this, some F2 progeny have been successfully developed. Nonetheless, there appear to be no reports detailing the practical development of perennial hybrids (Schelfhout et al. 2007). The sunflower (*Helianthus annuus*) is a vital oil crop species and a large annual forb in the Asteraceae family. Within the Asteraceae family, some genera, such as *Helianthus* and *Silphium*, include perennial species. Among the perennial species, *Helianthus maximiliani* and *Silphium integrifolium* are candidates for perennial sunflower crops. Agronomic research on Maximilian sunflower (*H. maximiliani*) as a potential perennial grain began at the Land Institute in the 1980s (Jackson 1990). Selection efforts, including those focused on seed size, resulted in a 240% increase in average seed size. By 2012, plants with a highly restricted branching habit had been developed (Van Tassel et al. 2014). *H. annuus* and *H. maximiliani* are diploid species ($2n= 17$) capable of hybridization, and cytogenetic analysis has revealed a high proportion of normal bivalents in hybrids, suggesting significant homology between the parental chromosomes (Jan 1997, Binsfeld et al. 2001). Therefore, the development of practical hybrids is anticipated. Tuberous sunflowers (*Helianthus tuberosus*), which are native to Japan, can be marginally cultivated for seed production, but the quantities are limited. Therefore, further research is required to determine whether interspecific hybridization could lead to improvements. Additionally, research on the evaluation of perennials and interspecific hybrid development is being conducted for other species, such as perennial cotton (Zhang et al. 2022), castor (Baldanzi et al. 2019), and flax (Tork et al. 2022).

Future prospects

Obstacles to stable food production are significantly influenced by both weather conditions and social circumstances. One major challenge is preparing for severe cold damage, which has historically led to famine. Large-scale volcanic eruptions and periodic fluctuations in solar activity are considered significant factors contributing to cold damage (Yamakawa et al. 1993). Historical records document events ranging from small-scale disruptions over decades to severe occurrences lasting several centuries. The severe famines associated with these events must be recognized as a potentially grave threat. In response to famine, cultivating tuber crops and short-growing-period crops such as common buckwheat has provided one avenue for survival. As an alternative approach, the development of perennial crops is considered a vital theme worthy of exploration. However, the development of perennial crops represents a technological challenge that counters certain aspects of plant evolution; for instance, in transitioning from warm eras without glacial periods to new eras characterized by such conditions, annual crops have been favored by natural selection over perennials. This is particularly pronounced in regions where frost or soil freezing occurs. In addition to the technical challenges of hybridization and the accumulation of useful genes, even if hybrids demonstrating sufficient growth potential are obtained, numerous hurdles remain to practical application. These include avoiding continuous cropping issues, preventing weediness, ensuring quality, and evaluating utility. Although these difficulties exist, as highlighted in this study, interspecies hybridization is emerging as a potential starting point for solutions. It is hoped that practical varieties will be developed in the future.

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