potassium supply can partially alleviate the adverse effects of shading on the growth of *F. thunbergii* and increase bulb biomass and yield under shading conditions, although these indicators still cannot fully recover to the level of the unshaded control (Liu et al., 2025a). Therefore, combining moderate shading with optimized nutrient supply is an important pathway for balancing light energy utilization, stress mitigation, and yield stability.

3.2 Effects of temperature changes on sprouting, leaf expansion, and bulb enlargement

Temperature is one of the core factors regulating the growth rhythm and phenological process of *F. thunbergii*. *F. thunbergii* has a biological preference for cool conditions, and its sprouting, emergence, leaf expansion, and bulb enlargement are closely related to temperature changes. Under suitable low-temperature and mild climatic conditions, seed bulbs can successfully break dormancy and sprout, aboveground growth is relatively uniform, and leaves expand fully, which is conducive to the formation of a good population structure. Studies have shown that temperature plays a key role in breaking bulb dormancy and initiating sprouting in *F. thunbergii*. Storage of *F. thunbergii* bulbs at 10°C for 30~45 days or at 4°C for 45~60 days is considered a critical period for dormancy release. During this process, the content of phenolic compounds decreases and related enzyme activities change, indicating that sprouting induction involves a temperature-dependent biochemical mechanism. Low-temperature pretreatment of in vitro-produced bulblets at approximately 5°C for several weeks can also promote uniform sprouting after transplantation, indicating that exposure to low temperature is important for successful emergence and population establishment (Marković et al., 2021).

Once dormancy is released, subsequent temperature conditions regulate leaf expansion and bulb enlargement by affecting carbon acquisition and assimilate allocation. Leaf expansion and vegetative growth stages are relatively sensitive to temperature. Suitable temperatures promote leaf expansion, root absorption, and photosynthesis, enabling plants to establish a strong vegetative growth foundation. When temperatures are too high, transpiration increases, water consumption accelerates, and leaves are prone to wilting, yellowing, or premature senescence, leading to decreased photosynthetic capacity. Meanwhile, high temperature may also alter the balance of carbon and nitrogen metabolism in plants, resulting in insufficient transport of assimilates to underground bulbs and ultimately affecting bulb enlargement and marketable yield. Studies on related *Fritillaria* species have shown that in geophytes such as *Fritillaria meleagris*, compared with 7°C, higher temperatures during post-dormancy growth, approximately 24°C, combined with gibberellin treatment can significantly increase bulb fresh weight and sprouting rate, whereas low-temperature conditions slow biomass accumulation (Figure 2) (Marković et al., 2020). Therefore, *F. thunbergii* does not require low temperatures throughout its entire growth cycle; rather, it requires appropriate low temperature to complete dormancy release, followed by moderately warm conditions to promote leaf expansion, photosynthesis, and bulb enlargement.

The bulb enlargement stage is the key period for yield formation in *F. thunbergii*, during which temperature conditions directly affect dry matter accumulation and underground organ development. A mild, stable environment with an appropriate diurnal temperature difference is conducive to the accumulation of organic matter through photosynthesis during the day and to reduced respiratory consumption at night, thereby promoting the transfer of more assimilates to the bulbs. If persistent high temperatures occur during this stage, the aboveground parts are prone to premature withering, the duration of bulb enlargement is shortened, and single-bulb weight decreases. In vitro culture studies have shown that under a 16 h light/8 h dark regime, approximately 25°C is the most favorable temperature for bulblet regeneration and early growth of *F. thunbergii*. Compared with continuous darkness at the same temperature, this condition better supports rapid leaf development and bulblet enlargement. Thus, temperature not only affects the progression of each growth stage of *F. thunbergii*, but also determines whether the plant can complete sufficient material accumulation within a limited growing period. Overall, the growth of *F. thunbergii* requires a “cool-warm” temperature sequence: sufficient low temperature to break dormancy, followed by moderately warm conditions to promote leaf establishment, photosynthesis, and bulb weight gain.