

biomass loss, and endophytic bacteria from *F. thunbergii* showed potential for nutrient promotion and biocontrol against *Fusarium* pathogens. Overall, the most promising path is an integrated system that combines rapid propagation, standardized quality evaluation, and ecological precision cultivation, thereby supporting the large-scale, high-quality, and sustainable modernization of *F. thunbergii* production.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Bhardwaj S., Kumari M., Chethan T., Hosamani M., Paul M., Moirangthem A., Dash A.P., and Verma S., 2025, Advances in micropropagation and tissue culture for horticultural crops: a review, *Plant Cell Biotechnology and Molecular Biology*, 26(11-12): 166-182.
<https://doi.org/10.56557/pcbmb/2025/v26i11-1210039>
- Chang H.C., Xie H.M., Lee M.R., Lin C.Y., Yip M.K., Agrawal D.C., and Tsay H.S., 2020, In vitro propagation of bulblets and LC-MS/MS analysis of isosteroidal alkaloids in tissue culture derived materials of Chinese medicinal herb *Fritillaria cirrhosa* D. Don, *Botanical Studies*, 61(1): 9.
<https://doi.org/10.1186/s40529-020-00286-2>
- Cheng X., Li D., Jiang Z., Qu C., Yan H., and Wu Q., 2023, Metabolite profiling and transcriptomic analyses demonstrate the effects of biocontrol agents on alkaloid accumulation in *Fritillaria thunbergii*, *BMC Plant Biology*, 23(1): 435.
<https://doi.org/10.1186/s12870-023-04459-6>
- Hamdeni I., Louhaichi M., Slim S., Boulila A., and Bettaieb T., 2022, Incorporation of organic growth additives to enhance in vitro tissue culture for producing genetically stable plants, *Plants*, 11(22): 3087.
<https://doi.org/10.3390/plants11223087>
- Hasnain A., Naqvi S.A.H., Ayesha S.I., Khalid F., Ellahi M., Iqbal S., Hassan M.Z., Abbas A., Adamski R., Markowska D., Baazeem A., Mustafa G., Moustafa M., Hasan M.E., and Abdelhamid M.M.A., 2022, Plants in vitro propagation with its applications in food, pharmaceuticals and cosmetic industries; current scenario and future approaches, *Frontiers in Plant Science*, 13: 1009395.
<https://doi.org/10.3389/fpls.2022.1009395>
- He R., Ma Q., Lu Y., and Jiang Z., 2021, Quality evaluation of *Fritillaria thunbergii* by high-performance liquid chromatography fingerprinting coupled with multicomponent quantitative analysis, *International Journal of Agriculture and Biology*, 25(1): 131-138.
<https://doi.org/10.17957/IJAB/15.1647>
- Huang L., Liang S., Luo L., Wu M., Fu H., and Zhong Z., 2024, Transcriptomic analysis reveals effects of fertilization towards growth and quality of *Fritillariae thunbergii* bulbus, *PLOS ONE*, 19(9): e0309978.
<https://doi.org/10.1371/journal.pone.0309978>
- Jiang J.M., Yu X.G., Wang W.J., Wang Z.H., Shao J., and Wang Z.A., 2019, Breeding and variety characteristics of a new variety of *Fritillaria thunbergii* “Zhebei 3”, *Zhongguo Zhong Yao Za Zhi* (China Journal of Chinese Materia Medica), 44(3): 448-453.
<https://doi.org/10.19540/j.cnki.cjcmm.20181204.005>
- Li H., Hung A., Li M., and Yang A.W.H., 2019, *Fritillariae thunbergii* bulbus: traditional uses, phytochemistry, pharmacodynamics, pharmacokinetics and toxicity, *International Journal of Molecular Sciences*, 20(7): 1667.
<https://doi.org/10.3390/ijms20071667>
- Liu J., Sheng X., Zhu Z., Zhang K., Yuan Q., Wang H., and Sui N., 2026, Co-application of biochar and organic fertiliser enhances the yield and quality of understory *Fritillaria thunbergii* Miq. by optimising soil and rhizosphere microecological structure, *Industrial Crops and Products*, 246: 123387.
<https://doi.org/10.1016/j.indcrop.2026.123387>
- Liu J., Zhu Z., Wang L., Yuan Q., Zhu H., Sheng X., Zhang K., Liang B., Jin H., Wang S., Weng W., Wang H., and Sui N., 2025, Regulation of steroidal alkaloid biosynthesis in bulbs of *Fritillaria thunbergii* Miq. by shading and potassium application: integrating transcriptomics and metabolomics analyses, *Biology*, 14(6): 633.
<https://doi.org/10.3390/biology14060633>
- Mansoor S., Iqbal S., Popescu S.M., Kim S.L., Chung Y.S., and Baek J.H., 2025, Integration of smart sensors and IoT in precision agriculture: trends, challenges and future perspectives, *Frontiers in Plant Science*, 16: 1587869.
<https://doi.org/10.3389/fpls.2025.1587869>
- Marković M., Trifunović Momčilov M., Uzelac B., Jevremović S., and Subotić A., 2021, Bulb dormancy in vitro-*Fritillaria meleagris*: initiation, release and physiological parameters, *Plants*, 10(5): 902.
<https://doi.org/10.3390/plants10050902>
- Marković M., Trifunović-Momčilov M., Radulović O., Paunović D.M., Antonić Reljin D.D., Uzelac B., and Subotić A., 2023, The effects of different auxin-cytokinin combinations on morphogenesis of *Fritillaria meleagris* using bulb scale sections in vitro, *Horticulturae*, 9(8): 910.
<https://doi.org/10.3390/horticulturae9080910>
- Mehbub H., Akter A., Akter M.A., Mandal M.S.H., Hoque M.A., Tuleja M., and Mehraj H., 2022, Tissue culture in ornamentals: cultivation factors, propagation techniques, and its application, *Plants*, 11(23): 3208.
<https://doi.org/10.3390/plants11233208>