REFERENCES

[1] NOAA National Centers for Environmental Information, "Monthly global climate report for april 2024," Published online May 2024; retrieved August 17, 2025, Apr. 2024. [Online]. Available: https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202413

[2] K. Abbass, M. Z. Qasim, H. Song, M. Murshed, H. Mahmood, and I. Younis, "A review of the global climate change impacts, adaptation, and sustainable mitigation measures," *Environmental science and pollution research*, vol. 29, no. 28, pp. 42 539–42 559, 2022.

[3] Food, A. O. of the United Nations, I. F. for Agricultural Development, U. N. C. Fund, W. F. Programme, and W. H. Organization, "The state of food security and nutrition in the world 2023: Urbanization, agrifood systems transformation and healthy diets across the rural–urban continuum," Online, Food and Agriculture Organization of the United Nations, et al., Tech. Rep., 2023, accessed August 17, 2025. [Online]. Available: https://openknowledge.fao.org/items/445c9d27-b396-4126-96c9-50b335364d01

[4] Food and Agriculture Organization of the United Nations, "Rome declaration on world food security and world food summit plan of action," Food and Agriculture Organization of the United Nations, Rome, Tech. Rep., November 1996. [Online]. Available: https://www.fao.org/4/w3613e/w3613e00.htm

[5] ——, "Food security," FAO Agriculture and Development Economics Division, Rome, Policy Brief Issue 2, June 2006, published with support from the FAO Netherlands Partnership Programme (FNPP) and the EC-FAO Food Security Programme. [Online]. Available: http://www.fao.org/es/esa/

[6] J. Berazneva and D. R. Lee, "Explaining the african food riots of 2007–2008: An empirical analysis," *Food Policy*, vol. 39, pp. 28–39, 2013.

[7] S. Cesco, P. Sambo, M. Borin, B. Basso, G. Orzes, and F. Mazzetto, "Smart agriculture and digital twins: Applications and challenges in a vision of sustainability," *European Journal of Agronomy*, vol. 146, p. 126809, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1161030123000771

[8] S. Fountas, B. Espejo-Garcia, A. Kasimati, M. Gemtou, H. Panoutsopoulos, and E. Anastasiou, " Agriculture 5.0: Cutting-Edge Technologies, Trends, and Challenges ," *IT Professional*, vol. 26, no. 01, pp. 40–47, Jan. 2024. [Online]. Available: https://doi.ieeecomputersociety.org/10.1109/MITP.2024.3358972

[9] R. Gund, C. M. Badgujar, S. Samiappan, and S. Jagadamma, "Application of digital twin technology in smart agriculture: A bibliometric review," *Agriculture*, vol. 15, no. 17, 2025. [Online]. Available: https://www.mdpi.com/2077-0472/15/17/1799

[10] F. Tao, H. Zhang, A. Liu, and A. Y. C. Nee, "Digital twin in industry: State-of-the-art," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 4, pp. 2405–2415, 2019.

[11] D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP Journal of Manufacturing Science and Technology*, vol. 29, pp. 36–52, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1755581720300110

[12] M. Grieves, "Digital twin: manufacturing excellence through virtual factory replication," *White paper*, vol. 1, no. 2014, pp. 1–7, 2014.

[13] M. Shafto, M. Conroy, R. Doyle, E. Glaessgen, C. Kemp, J. LeMoigne, and L. Wang, "Draft modeling, simulation, information technology & processing roadmap," *Technology area*, vol. 11, pp. 1–32, 2010.

[14] M. Singh, E. Fuenmayor, E. P. Hinchy, Y. Qiao, N. Murray, and D. Devine, "Digital twin: Origin to future," *Applied System Innovation*, vol. 4, no. 2, p. 36, 2021.

[15] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *Ifac-PapersOnline*, vol. 51, no. 11, pp. 1016–1022, 2018.

[16] M. Attaran and B. G. Celik, "Digital twin: Benefits, use cases, challenges, and opportunities," *Decision Analytics Journal*, vol. 6, p. 100165, 2023.

[17] S. R. Jaeger, "Vertical farming (plant factory with artificial lighting) and its produce: consumer insights," *Current opinion in food science*, vol. 56, p. 101145, 2024.

[18] T. Kozai, G. Niu, and M. Takagaki, *Plant factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. Academic press, 2019.

[19] W. Hu, T. Zhang, X. Deng, Z. Liu, and J. Tan, "Digital twin: A state-of-the-art review of its enabling technologies, applications and challenges," *Journal of Intelligent Manufacturing and Special Equipment*, vol. 2, no. 1, pp. 1–34, 2021.

[20] Q. Qi, F. Tao, T. Hu, N. Anwer, A. Liu, Y. Wei, L. Wang, and A. Y. Nee, "Enabling technologies and tools for digital twin," *Journal of Manufacturing Systems*, vol. 58, pp. 3–21, 2021.

[21] J. Monteiro, J. Barata, M. Veloso, L. Veloso, and J. Nunes, "Towards sustainable digital twins for vertical farming," in *2018 Thirteenth International Conference on Digital Information Management (ICDIM)*. IEEE, 2018, pp. 234–239.

[22] J. P. González, D. Sanchez-Londoño, and G. Barbieri, "A monitoring digital twin for services of controlled environment agriculture," *IFAC-papersonline*, vol. 55, no. 19, pp. 85–90, 2022.

[23] T.-H. Ko, H.-M. Lee, D.-H. Noh, C. JuHwan, and S.-W. Byun, "Design and implementation of a digital twin platform in vertical farming systems," in *2022 Thirteenth International Conference on Ubiquitous and Future Networks (ICUFN)*. IEEE, 2022, pp. 366–368.

[24] L. Wang, "Digital twins in agriculture: a review of recent progress and open issues," *Electronics*, vol. 13, no. 11, p. 2209, 2024.

[25] J. Liu, L. Wang, Y. Wang, S. Xu, and Y. Liu, "Research on the interface of sustainable plant factory based on digital twin," *Sustainability*, vol. 15, no. 6, p. 5010, 2023.

[26] R. Zhang, H. Zhu, Q. Chang, and Q. Mao, "A comprehensive review of digital twins technology in agriculture," *Agriculture*, vol. 15, no. 9, p. 903, 2025.

[27] M. Liu, S. Fang, H. Dong, and C. Xu, "Review of digital twin about concepts, technologies, and industrial applications," *Journal of manufacturing systems*, vol. 58, pp. 346–361, 2021.

[28] K. Chen, Y. Yuan, B. Zhao, L. Zhou, K. Niu, X. Jin, S. Gao, R. Li, H. Guo, and Y. Zheng, "Digital twins and data-driven in plant factory: an online monitoring method for vibration evaluation and transplanting quality analysis," *Agriculture*, vol. 13, no. 6, p. 1165, 2023.

[29] C. Mitsanis, W. Hurst, and B. Tekinerdogan, "A 3d functional plant modelling framework for agricultural digital twins," *Computers and Electronics in Agriculture*, vol. 218, p. 108733, 2024.

[30] G. Ochoa, "On genetic algorithms and lindenmayer systems," in *International Conference on Parallel Problem Solving from Nature*. Springer, 1998, pp. 335–344.

[31] I. Wohlgenannt, A. Simons, and S. Stieglitz, "Virtual reality," *Business & Information Systems Engineering*, vol. 62, no. 5, pp. 455–461, 2020.

[32] K. R. Walsh and S. D. Pawlowski, "Virtual reality: A technology in need of is research," *Communications of the Association for Information Systems*, vol. 8, no. 1, p. 20, 2002.

[33] A. Hamad and B. Jia, "How virtual reality technology has changed our lives: An overview of the current and potential applications and limitations," *International Journal of Environmental Research and Public Health*, vol. 19, no. 18, 2022. [Online]. Available: https://www.mdpi.com/1660-4601/19/18/11278

[34] G. R. Dixon, *Vegetable Brassicas and Related Crucifers*, ser. Crop Production Science in Horticulture. Wallingford, UK: CABI Publishing, 2006, vol. 14.

[35] P. Yusuk, S. Thumdee, P. Poonlarp, and D. Boonyakiat, "Effect of season and harvesting time on quality of organic pak choi (brassica rapa var. chinensis)," *Thai Journal of Agricultural Science*, vol. 51, no. 1, pp. 18–31, 2018.

[36] A. Kalisz, J. Kostrzewa, A. Sekara, A. Grabowska, and S. Cebula, "Yield and nutritional quality of several non-heading chinese cabbage (brassica rapa var. chinensis) cultivars with different growing period and its modelling," *Korean Journal of Horticultural Science and Technology*, vol. 30, no. 6, pp. 650–656, 2012.

[37] Ankit, S. K. Singh, A. Bora, B. J. Gogoi, and S. K. Dwivedi, "Performance evaluation of pak choi (brassica rapa subsp. chinensis) in different soilless cultivation methods," *Progressive Horticulture*, vol. 54, no. 1, 2022.

[38] J. Pirker, E. Loria, S. Safikhani, A. Künz, and S. Rosmann, "Immersive virtual reality for virtual and digital twins: A literature review to identify state of the art and perspectives," in *2022 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 2022, pp. 114–115.

[39] K. C. T. Fernandez, R. G. Baldovino, and R. K. C. Billones, "Digital twinning to predict harvest weight of hydroponically grown romaine lettuce," in *2022 IEEE 14th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*. IEEE, 2022, pp. 1–6.

[40] O. Mirbod, D. Choi, and J. K. Schueller, "From simulation to field validation: A digital twin-driven sim2real transfer approach for strawberry fruit detection and sizing," *AgriEngineering*, vol. 7, no. 3, p. 81, 2025.

[41] L. Xu, H. Yu, H. Qin, Y. Chai, N. Yan, D. Li, and Y. Chen, "Digital twin for aquaponics factory: Analysis, opportunities, and research challenges," *IEEE Transactions on Industrial Informatics*, vol. 20, no. 4, pp. 5060–5073, 2023.

[42] Z. Zhang, Z. Zhu, G. Gao, D. Qu, J. Zhong, D. Jia, X. Du, X. Yang, and S. Pan, "Design and research of digital twin system for multi-environmental variable mapping in plant factory," *Computers and Electronics in Agriculture*, vol. 213, p. 108243, 2023.

[43] E. H. Korkut and E. Surer, "Visualization in virtual reality: a systematic review," *Virtual Reality*, vol. 27, no. 2, pp. 1447–1480, 2023.

[44] S. N. Abdo, J. L. Hsu, C. Kapetanakis, D. L. Newman, L. K. Wright, and J. Bailey, "An exploration of spatial visualization skills: Investigating students' use of 3d models in science problems during think-aloud interviews," *Journal of chemical education*, vol. 101, no. 9, pp. 3624–3634, 2024.

[45] J. Jeong, A. Choi, D. Kang, and Y. K. Lee, "A comparative study of 2d vs. 3d chart visualizations in virtual reality," *Journal of Visualization*, vol. 28, no. 1, pp. 239–253, 2025.

[46] Y. Y. Cho, J. H. Lee, J. H. Shin, and J. E. Son, "Development of an expolinear growth model for pak-choi using the radiation integral and planting density," *Horticulture, Environment, and Biotechnology*, vol. 56, no. 3, pp. 310–315, 2015.

[47] X. Ding, H. Zhang, L. He, H. Jin, Q. Zhou, J. Yang, W. Zhu, J. Yu, and T. Qian, "Changes in leaf and growth of pak choi in a semi-closed greenhouse in eastern china," *HortScience*, vol. 57, no. 5, pp. 643–651, 2022.

[48] G. Buck-Sorlin, *Process-based Model*. New York, NY: Springer New York, 2013, pp. 1755–1755. [Online]. Available: https://doi.org/10.1007/978-1-4419-9863-7_1545

[49] L. Nouri, K. T. Azari, and M. Alaghmandan, "Development of algorithmic applications in architecture: A review and analysis of l-systems." *Bagh-e Nazar*, vol. 19, no. 116, 2023.

[50] P. Prusinkiewicz, M. Cieslak, P. Ferraro, and J. Hanan, "Modeling plant development with l-systems," in *Mathematical modelling in plant biology*. Springer, 2018, pp. 139–169.

[51] P. Prusinkiewicz and A. Runions, "Computational models of plant development and form," *New Phytologist*, vol. 193, no. 3, pp. 549–569, 2012.

[52] G. Buck-Sorlin, R. Hemmerling, O. Kniemeyer, B. Burema, and W. Kurth, "A rule-based model of barley morphogenesis, with special respect to shading and gibberellic acid signal transduction," *Annals of Botany*, vol. 101, no. 8, pp. 1109–1123, 2008.

[53] C. Fournier and B. Andrieu, "Adel-maize: an l-system based model for the integration of growth processes from the organ to the canopy. application to regulation of morphogenesis by light availability," *Agronomie*, vol. 19, no. 3-4, pp. 313–327, 1999.

[54] M. Ruiz-Ramos and M. I. Mínguez, "Alameda, a structural–functional model for faba bean crops: morphological parameterization and verification," *Annals of Botany*, vol. 97, no. 3, pp. 377–388, 2006.

[55] F. Okura, "3d modeling and reconstruction of plants and trees: A cross-cutting review across computer graphics, vision, and plant phenotyping," *Breeding Science*, vol. 72, no. 1, pp. 31–47, 2022.

[56] J. Guo, Z. Cheng, S. Xu, and X. Zhang, "Realistic procedural plant modeling guided by 3d point cloud," in *ACM SIGGRAPH 2017 Posters*, 2017, pp. 1–2.

[57] A. Chaudhury, C. Ward, A. Talasaz, A. G. Ivanov, M. Brophy, B. Grodzinski, N. P. Hüner, R. V. Patel, and J. L. Barron, "Machine vision system for 3d plant phenotyping," *IEEE/ACM transactions on computational biology and bioinformatics*, vol. 16, no. 6, pp. 2009–2022, 2018.

[58] Y. Yang, L. Zhong, S. Li, and A. Yu, "Research on the perceived quality of virtual reality headsets in human–computer interaction," *Sensors*, vol. 23, no. 15, p. 6824, 2023.

[59] W. Huang and R. D. Roscoe, "Head-mounted display-based virtual reality systems in engineering education: A review of recent research," *Computer Applications in Engineering Education*, vol. 29, no. 5, pp. 1420–1435, 2021.

[60] A. C. Firu, A. I. Tapîrdea, A. I. Feier, and G. Drăghici, "Virtual reality in the automotive field in industry 4.0," *Materials Today: Proceedings*, vol. 45, pp. 4177–4182, 2021.

[61] D. Chatterjee, S. Sadhu, D. Mondal, and D. Kalindi, "Use of virtual reality simulation practices for farmers training," *Madras Agricultural Journal*, vol. 112, no. March, p. 74–84, May 2025.

[62] J. A. Greig, B. Colclasure, S. Rampold, T. Ruth, and T. Granberry, "Enhancing agricultural education through virtual reality: Facilitation, application, reflection, and measurement in the classroom," *Advancements in Agricultural Development*, vol. 5, no. 2, pp. 64–80, 2024.

[63] R. Lasseur, S. Laurenson, M. Ali, I. Loh, and M. Mackay, "Designing profitable and climate-smart farms using virtual reality," *PLoS One*, vol. 18, no. 6, p. e0286723, 2023.

[64] D. Priadi and F. Nuro, "Seedling production of pak choy (brassica rapa l.) using organic and inorganic nutrients," *Biosaintifika: Journal of Biology & Biology Education*, vol. 9, no. 2, pp. 217–224, 2017.

[65] Badan Pusat Statistik Indonesia. (2024, 6) Produksi tanaman sayuran, 2022. Diakses pada 5 Oktober 2025. [Online]. Available: https://www.bps.go.id/id/statistics-table/2/NjEjMg==/produksi-tanaman-sayuran.html

[66] Y. Y. Cho and J. E. Son, "Estimation of leaf number and leaf area of hydroponic pak-choi plants (brassica campestns ssp, chinensis) using growing degree-days," *Journal of Plant Biology*, vol. 50, no. 1, pp. 8–11, 2007.

[67] M. A. G. A., F. Vexo, and D. Thalmann, *Virtual Characters*. London: Springer London, 2008, pp. 71–106. [Online]. Available: https://doi.org/10.1007/978-1-84800-117-6_4

[68] F. Tao and M. Zhang, "Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing," *IEEE access*, vol. 5, pp. 20 418–20 427, 2017.

[69] F. Tao, M. Zhang, Y. Liu, and A. Nee, "Digital twin driven prognostics and health management for complex equipment," *CIRP Annals*, vol. 67, no. 1, pp. 169–172, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0007850618300799

[70] S. K. Card, J. Mackinlay, and B. Shneiderman, *Readings in information visualization: using vision to think*. Morgan Kaufmann, 1999.

[71] S. Chen, *Plant Factory Technologies*. Cham: Springer International Publishing, 2022, pp. 1–10. [Online]. Available: https://doi.org/10.1007/978-3-030-89123-7_144-1

[72] J. von Neumann, "Method in the physical sciences," in *The Unity of Knowledge*, L. Leary, Ed. Garden City, NY: Doubleday & Company, 1955, pp. 157–164, reprinted in *The Neumann Compendium*, edited by F. Bródy and T. Vámos, World Scientific, 1995, p. 628; and in *John von Neumann Collected Works*, edited by A. Taub, Volume VI, pp. 491–498.

[73] Y.-P. P. Chen and R. M. Colomb, "Database technologies for l-system simulations in virtual plant applications on bioinformatics," *Knowledge and information systems*, vol. 5, no. 3, pp. 288–314, 2003.

[74] P. Room, J. Hanan, and P. Prusinkiewicz, "Virtual plants: new perspectives for ecologists, pathologists and agricultural scientists," *Trends in Plant Science*, vol. 1, no. 1, pp. 33–38, 1996.

[75] A. Barczak and H. Woźniak, "Comparative study on game engines," *Studia Informatica. System and information technology*, vol. 23, no. 1-2, pp. 5–24, 2019.

[76] G. D. Ghuge, "3d modelling: A review," *International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)*, vol. 3, no. 3, pp. 614–623, 2023. [Online]. Available: https://www.ijarsct.co.in

[77] L. Soni, A. Kaur, and A. Sharma, "A review on different versions and interfaces of blender software," in *2023 7th International Conference on Trends in Electronics and Informatics (ICOEI)*. IEEE, 2023, pp. 882–887.

[78] M. S. Hosen, S. Ahmmed, and S. Dekkati, "Mastering 3d modeling in blender: from novice to pro," *ABC Research Alert*, vol. 7, no. 3, pp. 169–180, 2019.

[79] G. J. Myers, C. Sandler, and T. Badgett, *The Art of Software Testing*, 3rd ed. Hoboken, New Jersey: John Wiley & Sons, Inc., 2011.

[80] R. E. Rice, S. P. Aagarwal, and P. T. Kortum, "Effects of task difficulty and presentation order in subjective usability measurement," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 67, no. 1. SAGE Publications Sage CA: Los Angeles, CA, 2023, pp. 2168–2172.

[81] J. Brooke *et al.*, "Sus-a quick and dirty usability scale," *Usability evaluation in industry*, vol. 189, no. 194, pp. 4–7, 1996.

[82] P. Vlachogianni and N. Tselios, "Perceived usability evaluation of educational technology using the system usability scale (sus): A systematic review," *Journal of Research on Technology in Education*, vol. 54, no. 3, pp. 392–409, 2022.

[83] M. Tory and T. Moller, "Evaluating visualizations: do expert reviews work?" *IEEE computer graphics and applications*, vol. 25, no. 5, pp. 8–11, 2005.

[84] B. Foundation, "Armature structure," Blender Manual, accessed: 2025-10-25. [Online]. Available: https://docs.blender.org/manual/en/2.80/animation/armatures/structure.html

[85] ——, "Shape keys introduction," Blender Manual, 2024, accessed: 2025-10-25. [Online]. Available: https://docs.blender.org/manual/en/2.80/animation/shape_keys/introduction.html

[86] Z. Sharfina and H. B. Santoso, "An indonesian adaptation of the system usability scale (sus)," in *2016 International Conference on Advanced Computer Science and Information Systems (ICACSIS)*, 2016, pp. 145–148.

[87] J. Sauro, "5 ways to interpret a sus score," Blog post, MeasuringU, Sep. 2018, https://measuringu.com/interpret-sus-score/. [Online]. Available: https://measuringu.com/interpret-sus-score/